

Good Agricultural Practices for greenhouse vegetable crops

Principles for Mediterranean climate areas



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Good Agricultural Practices for greenhouse vegetable crops

Principles for Mediterranean climate areas

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Preface

A very significant event in the world history of Agriculture is the domestication of plants by mankind. Instead of depending on wild growth, it was realized that the planting of seeds or cuttings allowed the propagation of the type of plants desired. Another important breakthrough resulted from the need to protect the domesticated plants from abiotic and biotic stress factors. Protected cultivation emerged as a way to protect crops from adverse weather conditions allowing year-round production and the application of an integrated crop production and protection management approach for better control over pests and diseases.

Greenhouse crop production is now a growing reality throughout the world with an estimated 405 000 ha of greenhouses spread over all the continents. The degree of sophistication and technology depends on local climatic conditions and the socio-economic environment.

The experience of greenhouse production, which emerged in northern Europe, stimulated development in other areas, including the Mediterranean, North America, Oceania, Asia and Africa, with various rates and degrees of success. It has been shown that a mere transposition of north European solutions to other parts of the world is not a valid process. Each environment requires further research, development, extension, training and new norms of application to meet local requirements.

During the last 20 years countries in the Mediterranean climate area have become increasingly competitive producers of greenhouse vegetables. During this time there has been a revolution in greenhouse production technology in terms of greenhouse design, type and quality of the plastic covering material, fertigation, mulch, use of high-yielding hybrids and cultivars, plant training and pruning techniques, integrated pest management, the use of pollinator insects, climate control, soil solarization etc. Only a few years ago, a yield of 100 tonnes per hectare of tomato in a greenhouse was considered a good performance. Today, for growers in Mediterranean climate areas, a harvest of 300 tonnes per hectare is not unusual.

Besides supplying the local markets, the production of greenhouse vegetables is greatly valued for its export potential and plays an important role in the foreign trade balance of several national economies in the Mediterranean region. However, the intensification of greenhouse crop production has created favourable conditions for many devastating pests and diseases. This has significantly increased the need for pesticide applications. At the same time, legislative measures and standards requirements regarding the quality and safety of vegetables have become

increasingly demanding. Consumer awareness has risen and the demand for pesticide-free products is a reality which cannot be ignored.

Since 1993, the Regional Working Group on Greenhouse Crops in the Mediterranean Region facilitated by the FAO's Plant Production and Protection Division has supported training and research and development initiatives to strengthen national capacities in upgrading the greenhouse crop sector in Mediterranean climate areas. This publication builds on experience gained through partnerships forged by the working group and represents the interpartner effort of two decades. It aims to summarize the knowledge and practical experiences of scientists from the Near East and North Africa region, specifically from Algeria, Cyprus, Egypt, Jordan, Lebanon, Libya, Malta, Morocco, the Syrian Arab Republic, Tunisia and Turkey and in collaboration with the Commission of Protected Cultivation of the International Society for Horticulture Science (ISHS) and a worldwide panel of subject matter specialists.

This technical document intends to illustrate the benefits that can be drawn from an "integrated production and protection" (IPP) approach linking production technologies and plant protection practices to minimize the use of pesticides and adopting "sustainable intensification" of greenhouse crop production as the guiding principle. It is in line with the new FAO "Save and Grow" paradigm that helps to limit agriculture's impact on climate change and strengthens resilience of open-field and greenhouse farming systems to socio-economic and climate risks.

It is believed that greenhouse crop production is destined to play an increasingly important role in the Mediterranean climate environment as a means for sustainable crop intensification leading to optimization of water-use efficiency in an environment of water scarcity in addition to better control of product quality and safety, in line with the market demand, standards and regulations.

By sharing their knowledge and experience, the authors of this publication wish to sustain the competitiveness of the vegetable greenhouse sector in the Mediterranean climate areas and contribute to its further development to the benefit of growers, consumers and the environment.

This publication discusses the principles of Good Agricultural Practices (GAP) as they may be applied to greenhouse farming in the Mediterranean climate areas. It illustrates different aspects of greenhouse crop production and protection with special emphasis on greenhouse technologies, design and climate control, cropping systems, in particular those practices which help reduce pests and diseases incidence in crops, integrated pest management, the use of adapted cultivars, and the need for traceability and product labelling.

The guidebook is expected to serve as a training guide for trainers and a resource document for advanced growers and stakeholders of the greenhouse vegetable value chain. It is also a valuable source of information for programme managers, international and multilateral development organizations, NGOs and the private sector – as well as researchers, advisors and professionals in greenhouse agriculture. We trust that it will help to further strengthen the work of the FAO-facilitated Regional Working Group on Greenhouse crops in the Mediterranean Region.

Abdessalam Ould Ahmed

FAO Assistant Director-General and Regional Representative
Office of the Near East

List of acronyms and abbreviations

AAP	Air acidification potential
ADI	Acceptable daily intake
ADP	Abiotic depletion potential
AESA	AgroEcoSystem Analysis
AFP	Air-filled pore space
AGN	FAO Food Safety and Quality Division
AGP	FAO Plant Production and Protection Division
ALARI	Arid Land Agricultural Studies and Research Institute
AoP	Areas of protection
ARI	Agricultural Research Institute
ASABE	American Society of Agricultural and Biological Engineers
ASEAN	Association of Southeast Asian Nations
ATP	Adenosine triphosphate
BER	Blossom end rot
BSI	British Standards Institution
CA	Controlled atmosphere
CB	Certification body
CEC	Cation exchange capacity
CED	Cumulative energy demand
CEN	European Committee for Standardization
CFD	Computational fluid dynamics
CGMMV	Cucumber green mottle mosaic virus
CHP	Combined heat and power
CI	Chilling injury
CMV	Cucumber mosaic virus
CNL	Compensated no leakage
CPCC	Control Points and Compliance Criteria
CVYV	Cucumber vein yellowing virus
CWSI	Crop Water Stress Index
CYSDV	Cucurbit yellow stunting disorder virus

DE	Delivery efficiency
DFT	Deep flow technique
DIF	Day-night temperature difference
DT	Day temperature
DTPA	Diethylene triamine pentaacetic acid
DU	Distribution uniformity
DWC	Deep water culture
EAW	Easily available water
EBA	Ethylene butyl acrylate
EBI	Ergosterol biosynthesis inhibitor
EC	Electrical conductivity
EDDHA	Ethylene diamine di-o-hydroxyphenylacetic acid
EDTA	Ethylene diamine tetraacetic acid
EPC	Electronic product code identification
EPS	Effective pore space
ET	Economic threshold
ETc	Crop evapotranspiration
ETo	Reference evapotranspiration
EUP	Eutrophication potential
EVA	Ethylene vinyl acetate
EW	Equivalent weight
FDR	Frequency domain reflectometer
FE	Farm efficiency
FFS	Farmer field school
FH	Float hydroponics
FU	Functional unit
FW	Fresh weight
FYM	Farmyard manure
GAP	Good agricultural practice
GFT	Gravel film technique
GGN	GLOBALG.A.P number
Gm	Granular matrix
GMO	Genetically modified organism
GMP	Good manufacturing practice

GRIS	Greenhouse Information System
GWP	Global warming potential
HACCP	Hazard analysis and critical control point
HAF	Horizontal airflow
HEDTA	Hydroxyethyl ethylene diamine triacetic acid
IAA	Indoleacetic acid
ICS	Inductively coupled plasma
IE	Irrigation efficiency
IFA	Integrated farm assurance
IGR	Insect growth regulator
IOBC	International Organization for Biological Control of Noxious Animals and Plants
IPM	Integrated pest management
IPPM	Integrated production and pest management
IR	Infrared
IRTA	Institute for Food and Agricultural Research and Technology
IS	Irrigation scheduling
ISHS	International Society for Horticultural Science
K _c	Crop coefficient
K _p	Pan coefficient
LAI	Leaf area index
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low density polyethylene
LER	Land equivalency ratio
LLDP	Linear low density polyethylene
LP	Local practice
MA	Modified atmosphere
MBr	Methylbromide
MOA	Ministry of Agriculture (Jordan)
MRL	Maximum residue level
NCARE	National Center for Agricultural Research and Extension
NFT	Nutrient film technique
NIR	Near infrared

NPV	Nuclear polyhedrosis virus
NT	Night temperature
NUE	Nitrogen-use efficiency
PAR	Photosynthetically active radiation
PDCA	Plan-Do-Check-Act
PDSA	Plan-Do-Study-Act
PE	Polyethylene
PepMV	Pepino mosaic virus
PGR	Plant growth regulator
PHU	Produce handling unit
PMMA	Polymethyl methacrylate
PMU	Production management units
PVY	Potato virus Y
QMS	Quality management system
QR	Quick response
RDWC	Recirculating deep water culture (system)
REI	Re-entry interval
RFID	Radio frequency identification
RH	Relative humidity
RIS	Relative irrigation supply
RNA	Ribonucleic acid
SAR	Sodium adsorption ratio
SAS	Safety access system
SCIS	Soilless Culture Information System
SNFT	Super nutrient film technique
SOM	Soil organic matter
SOP	Standard operation practice
STV	Salinity threshold value
SYD	Salinity yield decrease
TCP	Technical Cooperation Programme
TDR	Time domain reflectometer
TDR	Time domain refractometry
TDS	Total dissolved solids
TDT	Time domain transmissiometry

TI	Temperature integration
TMV	Tobacco mosaic virus
TPS	Total pore space
TSWV	Tomato spotted wilt virus
TYLCV	Tomato yellow leaf curl virus
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UV	Ultraviolet
VPD	Vapour pressure deficit
YSD	Yellow shoulder disorder
WBC	Water buffer capacity
WE	Watering efficiency
WFT	Western flower thrip
WFS	Wood fibre substrate
WP	Water productivity
WPRS	West Palaeartic Regional Section (IOBC)
WUE	Water-use efficiency
ZYMV	Zucchini yellow mosaic virus

1. Regional Working Group on Greenhouse Crop Production in the Mediterranean Region: History and development

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FAO'S PLANT PRODUCTION AND PROTECTION DIVISION (AGP): APPROACH AND ROLE IN PROMOTING REGIONAL COOPERATION IN SUPPORT OF GREENHOUSE CROP PROTECTION

In line with the “Save and Grow” concept, AGP works to strengthen global food security by promoting sustainable crop production intensification, which aims at producing more from the same area of land while conserving resources, reducing negative impacts on the environment and enhancing natural capital and the flow of ecosystem services.

AGP's mandate is to enhance and strengthen:

- effective and strategic decisions that increase crop production using an ecosystem approach and nutrition-sensitive crop diversification;
- national capacities to monitor and respond effectively to transboundary and other important outbreaks of pests;
- policies and technologies appropriate to needs of member countries to reduce the negative impact of pesticides; and
- conservation and sustainable use of plant genetic resources with strong linkages between conservation, plant breeding and seed sector development.

As part of its programme areas, AGP supports the development of greenhouse technology for horticulture and high-value crops as a means for sustainable crop intensification. To this effect, a Regional Working Group was created 20 years ago, in 1993, to enhance south-south cooperation among the national institutions

and scientists from Near East and North Africa (NENA) countries ¹ and to facilitate interactions with cooperating scientists and institutions from northern countries, such as Belgium, France, Germany, Greece, Italy and Spain.² Together, they formed a network to enhance intercountry cooperation for the improvement of greenhouse crop production technology in the Mediterranean region. In these countries, protected cultivation is continuously expanding leading to improved water-use efficiency, increased productivity per unit input and land, improved product quality, reduced use of pesticides as a result of integrated pest and disease control. Simple tunnel-type greenhouses and more sophisticated structures are evolving side by side depending on the cost-effectiveness. Plastic film is the predominant covering material in Mediterranean climate areas. Out of an estimated 220 000 ha of greenhouses in the Mediterranean countries, 90 percent are covered with plastic and 10 percent with glass.³

The Working Group has been focusing its activities in three main areas:

- Information management and dissemination
- Training and demonstration
- Project formulation and implementation

SCOPE OF THIS PUBLICATION AND MAIN OBJECTIVES

The publication of *Good agricultural practices for greenhouse vegetable crops: Principles for Mediterranean climate areas* is a major achievement and also a key milestone of the FAO Regional Working Group on Greenhouse Production in the Mediterranean Region. Its scope is to capitalize the know-how and experiences of the FAO network of scientists which since the creation of the Regional Working Group have studied and debated a wide range of crop- and technology-related aspects of greenhouse crop production and protection.

The main objectives of this publication are:

- Provide a compilation of greenhouse production practices and technologies presently in use in Mediterranean climate areas that have helped increase vegetable production, productivity and quality.
- Provide recommendations on good agriculture practices based on the current best knowledge of the different crop and technology aspects for greenhouse vegetable cultivation in Mediterranean climate areas.

¹ Algeria, Cyprus, Egypt, Jordan, Lebanon, Libya, Malta, Morocco, the Palestinian Authority, the Syrian Arab Republic, Tunisia and Turkey.

² Please refer to p. 9 for the comprehensive list of cooperating scientists and institutions.

³ Tuzel, Y. and Leonardi, C. 2010. Protected cultivation in Mediterranean region: trends and needs. *Journal of Ege University Faculty of Agriculture*, 46(3): 215–223.

The document is in line with the new FAO “Save and Grow” paradigm that advocates the sustainable intensification of farming systems and strengthens their resilience to socio-economic and climate risks. The publication is meant to be a reference document for scientists, teachers and students, as well as private sector entrepreneurs. It is proposed as a training support document for upgrading the technical know-how of trainers and pilot growers as well as other actors in the greenhouse vegetables value chain in Mediterranean climate areas.

ORIGIN AND OPERATIONAL MODALITIES OF THE GREENHOUSE REGIONAL WORKING GROUP

The premises leading to the establishment of the FAO Working Group in the Mediterranean Region date back to February 1984. On the occasion of the ISHS Symposium on “Plastics for Horticulture in the Mediterranean Region” in Hammamet, Tunisia, the decision was made to prepare a position paper on the greenhouse production technology in the Mediterranean region based on the contributions of selected collaborators.

In September 1984, following a meeting with the Faculty of Horticulture at the State University of Gembloux, Belgium, an agreement was reached on the content and authors of a position paper entitled “Intensification of Horticulture Crop Production under Protected Cultivation in the Mediterranean Region”. In June 1985 the members of the drafting committee met in Gembloux to review the first draft under the joint supervision of Professor André Nisen, Faculty of Horticulture, Gembloux and Professor Giuseppe Lamalfa, University of Catania, Italy. The advanced draft was discussed in December 1985 during the ISHS workshop on “Protected Cultivation of Solanaceae Crops” in Faro, Portugal. The document was finally published in 1988 as the FAO AGP Technical Paper No. 90, initially in English and subsequently translated into French, Spanish and Arabic.

The actual establishment of the FAO Working Group on Greenhouse Crop Production in the Mediterranean Region, referred to as the WG, emerged from the recommendation formulated by the participants at the Expert Consultation Meeting on Protected Cultivation convened by Dr Abderahmane Hilali, Director of the Complexe Horticole (Institut Hassan II) in Agadir, Morocco in November 1993. The WG group is composed of scientists and decision-makers representing 12 countries from the Near East and North Africa region, namely Algeria, Cyprus, Egypt, Jordan, Lebanon, Libya, Malta, Morocco, the Palestinian Authority, the Syrian Arab Republic, Tunisia and Turkey.

As a result of a consultation process, the group members agreed on the scope, objectives and operational modalities for the WG. Realizing the complexity and the interaction of different disciplines for successful greenhouse crop management, they recommended that the scope of the WG should be to promote an “integrated approach” for sustainable greenhouse crop production intensification aiming at

improved product quality and safety with a view to reducing the use of pesticides and applying alternative methods for pest and disease control. The concept of integrated production and protection (IPP) was officially introduced by the WG – as a precursor of the GAP concept – on occasion of the International Symposium on Integrated Production and Protection of Horticultural Crops, convened by Dr Abdelhaq Hanafi (then Professor at Complexe Horticole of IAV Hassan) in Agadir, Morocco, in May 1997.

The WG members adopted the following three types of interrelated activities for the programme of the WG:

- Assessment of greenhouse production technologies for transfer to growers
- Strengthening of capacity building
- Implementation of joint research and development initiatives

The disciplines to be covered were grouped in four thematic areas (TA), each animated by a technical coordinator (TC).

Disciplines covered

- **TA1:** Irrigation, fertigation, soilless culture (**TC:** Ayman Abou Hadid, Egypt)
- **TA2:** Greenhouse design, covering materials, climate control, including geothermal water use (**TC:** Abdelaziz Mougou, Tunisia)
- **TA3:** IPP: Integrated production and protection management (**TC:** Abdelhaq Hanafi, Saudi Arabia)
- **TA4:** Production economics, quality requirements, crop diversification, organic horticulture (**TC:** Yuksel Tuzel, Turkey)

The activities in the four thematic areas were grouped into three categories:

- Information exchange
- Training and field demonstrations
- Project formulation and implementation

From an operational point of view, the WG activities are facilitated by a WG coordinator, belonging to one of the participating countries and with an office term of 2 years. The WG programme is discussed at the WG coordinating meeting held every 2 years to review the progress and achievements in the past biennium, agree on a work plan for the coming biennium and elect the WG coordinator. Most of the activities are implemented by countries drawing on their own resources or with project support. The coordinating meeting is hosted by the country of the “incoming” regional coordinator elected at the previous coordinating meeting.

ACTIVITIES, RESULTS AND ACHIEVEMENTS OF THE WORKING GROUP

Capacity building has been pursued through a series of FAO-sponsored technical workshops. As a group, the network members play a leading role in promoting the exchange of information on greenhouse crop technology and have been able to organize several international symposia, often in conjunction with the Commission Protected Cultivation of the International Society for Horticulture Science:

- Integrated production and protection (IPP) of horticulture crops, Agadir Morocco, 6–9 May 1997
- Strategies towards sustainability of protected cultivation in mild winter climate, Antalya, Turkey, 3–5 Nov. 1997
- Growing media and hydroponics, Thessaloniki, Greece, 4–5 Sept. 1999
- Greenhouse floriculture, production and export of cutflowers, Tunis, Tunisia, 9–10 June 2000
- Greenhouse vegetable production standards for quality and safety, Beirut, Lebanon, 6–7 May 2001
- Vegetable breeding and seed production, Cairo, Egypt, 12–16 Dec. 2001
- Organic greenhouse vegetable production, Amman, Jordan, 28–29 Jan. 2002
- Protected cultivation in mild winter climate: product and process innovation, Ragusa, Italy, 5–8 Mar. 2002
- Flowers for the future, Izmir, Turkey, 7–11 Oct. 2002
- Integrated greenhouse production and protection (IGPP), Beirut, Lebanon, 8–9 Mar. 2003
- Soilless culture technologies, Izmir, Turkey, 5–6 Mar. 2004
- Greenhouse cooling, Almería, Spain, 23–24 May 2006
- Sustainable greenhouse crop production technologies in mild winter climates, Antalya, Turkey, 6–11 April 2008

Exchange of information has been facilitated through the publication of technical documents and proceedings of workshops and symposia, which have been posted on the WG Web site <http://www.NenaGreenhousesFao.org>. The WG has produced the following documents:

- Country surveys and technical recommendations for the greenhouse crop sector in Cyprus, Egypt and the Syrian Arab Republic
- Technical guidelines on irrigation management
- Practical guidelines for cut-flower production in Tunisia

Some 3 200 datasets on the performance of horticulture cultivars in greenhouse cultivation have been inserted in Hortivar ⁴ as well as 39 “Good Morning Horticulture” messages. The countries have submitted 64 pairs of “IPP cards”, illustrating GAPs for greenhouse crops, which have been uploaded in Hortivar.

Templates have been designed and statistical information compiled on soilless culture systems in the Mediterranean countries in the Soilless Culture Information System (SCIS). Templates and statistical information on the greenhouse crop sector in Mediterranean countries has also been compiled in the Greenhouse Information System (GRIS). Both SCIS and GRIS have been integrated into Hortivar. Research for development has been strengthened and transfer of know-how to growers has been facilitated through the formulation and implementation of field projects.

The WG, with the assistance of FAO, has been able to formulate research-development projects and has obtained funding from EU, UNDP and TCP.

The FAO regional project, **TCP/INT/0165** established demonstration and training greenhouses in each of the participating countries. The objective of the project was to prepare growers to join GAP schemes like GLOBALG.A.P. by demonstrating and providing training for the adoption of integrated production and protection management (IPP) in greenhouse crops, aiming at healthy and high quality produce, sustainable productivity and reduced use of pesticides.

EU-funded **ECOPONICS** project, “Efficient water use through environmentally sound hydroponic production of high quality vegetables for domestic and export markets in Mediterranean countries” (2002–06). The project investigated simplified, economical and water-use-efficient hydroponics systems. Under the scientific coordination of the Technical University of Munich, it demonstrated the economic feasibility of ECOPONICS technology for vegetable enterprise development in Jordan, Turkey, Egypt and Morocco. It produced a set of tools – “standard operation practices” (SOPs) – for farmers, technicians and extension specialists, highlighting the advantages in relation to water management, salinity and product quality compared with traditional cultivation practices for export and domestic markets

TCP/TUN/8823. The project succeeded in demonstrating the potential of flower diversification options in order to capture export market niches and to supply the local market demand. Cost-benefit studies have been carried out to establish the comparative advantage of specific flower crops and farmers have been trained in applying improved and intensified cultivation practices.

⁴ Hortivar: FAO’s database on the performances of horticulture cultivars and platform for access to and sharing of information on the horticulture sector in general.

TCP/LEB/0067 (phase I) followed by **TCP/LEB/2906 (phase II)** “Rehabilitation of greenhouse vegetable production standards for safety and quality”. The overall objective is to restore small-scale farmers’ capability to produce high quality and safe vegetables under protected cultivation. The immediate objective of the project was to demonstrate “in field” cropping seasons by *in situ* demonstrations of improved production technologies and cultivation practices aimed at increasing vegetable yields and product safety and quality, lowering production costs, adopting more efficient greenhouse design and avoiding the disadvantages of the traditional greenhouse.

UNDP/EGY/95/002 “Protected cultivation”. The objectives of the agriculture strategy in Egypt are to increase agricultural productivity per unit of land and water through more efficient use of limited resources, reduction in the cost of production and thereby increase in the national output and farmers’ incomes. To fulfil these objectives, the project was designed to support the development and adoption of new technologies. Protected cultivation and soilless culture were recognized as efficient and promising technologies for attaining the set objectives.

CAPITALIZATION

On occasion of the Sixth WG Coordinating Meeting, held in Amman, Jordan in December 2006, the participants considered that the time was appropriate to take stock of the information accumulated and the experiences gained since the publication of the FAO AGP Technical Paper No. 90. They recommended that FAO take the lead in compiling a multi-author technical document which would serve the double purpose of compiling the know-how gained and making it available to growers and stakeholders in the greenhouse crop sector in the NENA region with a view to sustaining its competitiveness.

The overall guidelines and the identification of potential authors for the drafting of a publication on “Good Agricultural Practices (GAP) for greenhouse vegetable crops: Principles for Mediterranean climate areas” were elaborated on occasion of an FAO-ISHS workshop, which took place in June 2009 at the International Symposium on High Technology for Greenhouse Systems, Greensys 2009, hosted by the University of Laval, Quebec, Canada. Subsequently, an expert meeting was convened in Amman, Jordan in May 2010, which brought together the lead authors and allowed to discuss further the scope and target audience of the publication and to elaborate the table of contents. The members of the drafting committee met in Lisbon in August 2010 on occasion of the International Horticulture Congress to discuss and review the progress on the drafting of the document followed by a second business meeting in June 2011 on occasion of the Greensys Symposium in Halkidiki, Greece.

Editing took place during 2012. The final draft version was shared with the authors and participants at the International Workshop on “Good Agriculture

Practices – GAP – for greenhouse crops in the Mediterranean region”, jointly convened by ISHS, NCARE and FAO from 9 to 12 December 2012 in Jordan. Early 2013 allowed for a final peer review, proofreading and printing.

THE WAY FORWARD

The activities of the FAO Regional Working Group on Greenhouse Crop Production in the Mediterranean Region has undoubtedly impacted on the improvement of the greenhouse production sector in the NENA countries and has contributed to its mutation from a somewhat empiric activity into a professional enterprise with scientific bases.

The WG members are committed to continuing their cooperation and determined to seek opportunities to jointly implement research and development projects of common interest in support of the greenhouse crop sector in the Mediterranean climate areas. As a network of scientists, they will pursue their interaction with FAO and serve as a resource for information exchange, training and capitalization of know-how.

RECOMMENDED READING

Proceedings and technical country reports of the Working Group coordinating meetings held in:

- Agadir, Morocco, Nov. 1993
- Cairo, Egypt, 15–16 Dec. 1995
- Izmir, Turkey, 6–7 Nov. 1997
- Catania, Italy, 16–18 Dec. 1999
- Beirut, Lebanon, 4–6 Feb. 2002
- Nicosia, Cyprus, 13–14 Nov. 2003
- Amman, Jordan, 19–20 Dec. 2006

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2. Greenhouse site selection

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INTRODUCTION

In recent decades, greenhouse area has risen worldwide, due mainly to the increased use of plastic greenhouses for growing vegetable crops. Site selection is a key factor for profitable and sustainable greenhouse production. The main factors determining location and site selection of a greenhouse production area are: cost of production, quality of produced yield, and transportation cost to markets (Nelson, 1985; Castilla, 2007). Obviously, cost and quality of production depend on the local climate and the greenhouse growing conditions. The level of investment in technology (simple or sophisticated greenhouses and equipment), as well as management, depends primarily on the local climate.

Nowadays, long distance transportation means that production areas may be located far from major consumption centres, enabling the development of greenhouse industries in many climatically favourable areas around the world, such as the coastal zones of the Mediterranean Basin (Plate 1). In addition to transportation, marketing (standardization, packing etc.) also affects the overall cost of the products; they tend to be similar for different commodities coming from different geographical origins, but which compete in the same markets (Castilla *et al.*, 2004).

This chapter examines the climatic conditions required for the production of greenhouse crops, in particular vegetables.

GREENHOUSE MICROCLIMATE MODIFICATION

From a historical point of view, the initial objective of greenhouse cultivation was to grow heat-demanding species during the winter season in temperate countries, i.e. countries with a cold winter season. Inside greenhouses more favourable temperatures may be reached during the cold season, thanks to the windbreak effect and the



Plate 1
Poniente area (Almería, Spain)

**Plate 2***Banana crop in a greenhouse*

greenhouse effect. During the warm season, especially in the Mediterranean and tropical areas, where there is high solar radiation and the temperature exceeds the recommended maximum threshold level, the greenhouse effect has an adverse impact on the microclimate and crop performance. However, these negative effects are to some extent compensated for by the shading effect and can be regulated to a certain extent by proper ventilation and/or cooling of the greenhouse.

The greenhouse effect is the result of two different effects:

- a confinement effect, resulting from the decrease in the air exchanges with the outside environment; and
- an effect caused by the existence of a cover characterized by its low transparency to far infrared radiation (emitted by the crop, the soil and the inner greenhouse elements), but its high transparency to sunlight.

The use of cladding greenhouses with screens (nets) throughout the year, instead of plastic films, has become common practice in recent years in areas of very mild temperature (low latitudes) and in areas where temperatures are very mild in selected periods (medium latitudes in spring and summer). In these “screenhouses”, the greenhouse effect is minimal, as the confinement effect is very limited and sunlight is reduced (as screens’ transparency to sunlight is, normally, lower than in conventional greenhouse plastic cladding films). This minimal greenhouse effect varies according to the characteristics of the screens (permeability for air exchanges with the outside environment and transparency to sunlight), while the shading and windbreak effects prevail. Screenhouses do not protect crops from rainfall, as their cover is permeable, but they can reduce the damage caused by heavy rain and hail.

**Plate 3***Year-round supply of high-quality products*

GREENHOUSE PRODUCTION STRATEGIES

When planning the installation of a greenhouse, two main questions must be answered (Jensen and Malter, 1995):

- Where will the production be marketed (domestic or export markets or both)?
- What type of commodities will be produced (edible or ornamentals)?

In general, optimum climatic conditions and low production costs (with good quality) are key to the selection of a location; transportation costs are also an important consideration when markets are far away (Castilla, 2007). Other technical and socio-economic aspects (water and electricity supply, labour availability etc.) also influence production costs and competitiveness (Castilla and Hernandez, 2005).

There is currently a high demand from consumers for a year-round supply of quality products (Plate 3), conditioning the production strategies in the greenhouse industry. Greenhouse crops in mild winter climates, such as in the Mediterranean area, cannot be grown all year round with high quality. The challenge of supplying high quality vegetables all year round can be met by adopting one of two basic strategies:

- Growing in high-tech greenhouses, avoiding strong dependence on the outdoor climate.
- Growing in two or more locations with complementary harvesting periods, enabling a continuous and coordinated year-round supply to markets (Castilla and Hernandez, 2007).

The second alternative (using different locations, usually with different greenhouse technological levels) is an increasingly adopted strategy.

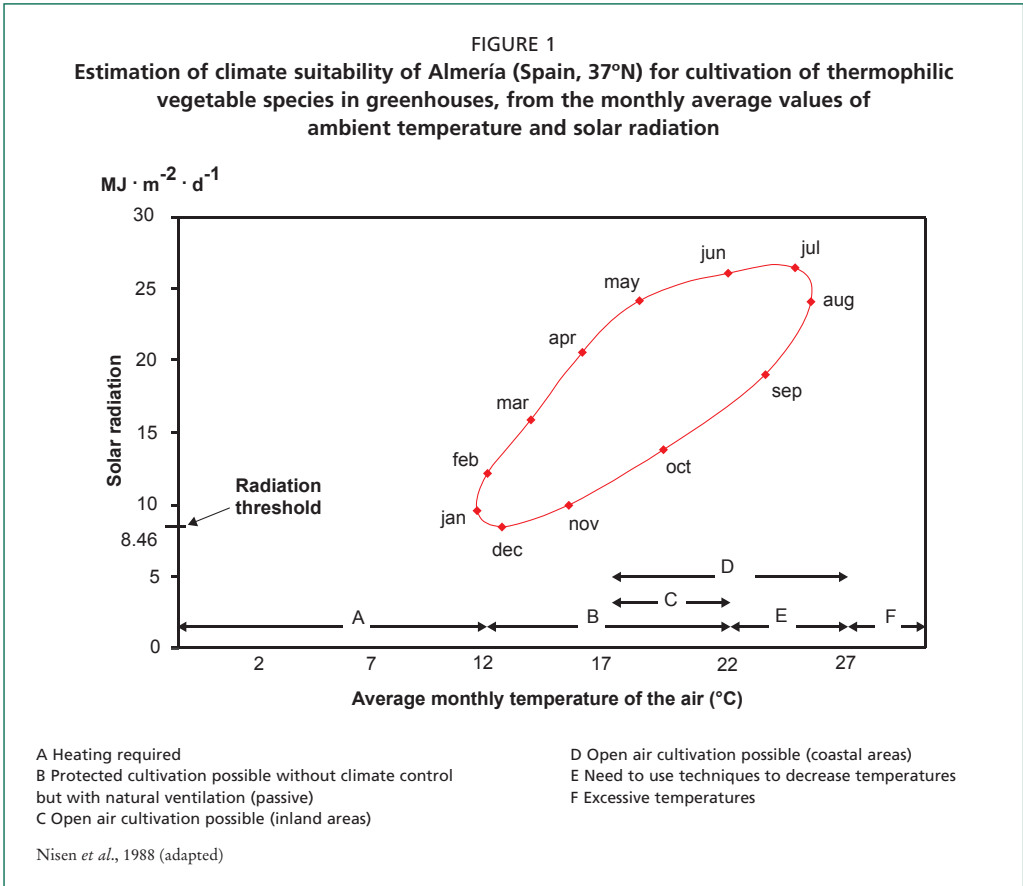
In some regions, including the Mediterranean, adapting plants to a suboptimal environment has in the past been the most common production strategy. In contrast, in northern Europe, the favoured approach has been to optimize the greenhouse environment in order to reach maximum potential yields. Nowadays, market globalization has led to greater competitiveness; it is therefore necessary to increase the quality of greenhouse products through better climate control (Castilla and Montero, 2008).

CLIMATIC SUITABILITY FOR GREENHOUSE VEGETABLE PRODUCTION

Introduction

Today's greenhouse technologies mean it is possible to cultivate all horticultural species in any region of the world, provided that the greenhouse is properly designed and equipped to control the climatic parameters. However, for profitable and sustainable cultivation of the target crop, much stricter selection of the region is necessary, on the basis of climatic conditions and the requirements of the selected horticultural crop.

Solar radiation is the main climate parameter needed to evaluate the climate suitability of a region for protected cultivation. Day length and solar radiation intercepted by a horizontal surface during daytime hours are measured to determine total daily solar radiation. Another basic climate parameter is ambient temperature. The stability of both values in different months of the year enables



the representation of their mean monthly values (obtained by averaging data sets for several years) for a given location in the climate diagram, which represents the location's climate (Figure 1).

Other climate parameters, such as soil temperature (closely linked to air temperature), wind, rainfall and air composition (humidity and CO₂), influence to a lesser degree the evaluation of climate suitability.

The type of greenhouse adopted depends on the region's climatic characteristics and on the crop requirements. For example, in a region with a tropical humid climate, where protection from rain is the greenhouse's main purpose (prevalence of the umbrella effect), the type of construction preferred may be different from that desirable in a semi-desert or Mediterranean climate region (Plate 4).

Climatic requirements of vegetables

The most commonly grown species in greenhouses are vegetables with medium thermal requirements (tomato, pepper, cucumber, melon, watermelon, marrow,

green bean, eggplant); the aim is to extend the growing calendars beyond the conventional open-air cultivation season, and thus increase profitability (Plate 5). Nowadays, the production of greenhouse crops in geographical areas without suitable climate conditions, is highly questionable since it entails significant and expensive artificial climate control. In any case, economic results determine the final selection of a greenhouse project location.

The indicated species, traditionally grown in the warm season, are adapted to average ambient temperatures ranging from 17 to 28 °C, with limits of 12 °C (minimum) and 32 °C (maximum) (Nisen *et al.*, 1988). They are sensitive to the cold and suffer irreversible damage with frosts.

Temperatures persistently below 10–12 °C over several days affect productivity, as do temperatures above 30 °C (in the case of dry air) or 30–35 °C (in the case of high air humidity) (Nisen *et al.*, 1988). Daily variation between day and night average temperatures (thermal periodicity) is required for proper physiological functioning. These thermal differences are between 5 and 7 °C (Nisen *et al.*, 1988).

The minimum daily radiation requirements of these species are estimated at around 8.5 MJ m⁻² day⁻¹ (equivalent to 2.34 kWh m⁻² day⁻¹) during the three shortest months of year (November, December and January in the Northern Hemisphere; May, June and July in the Southern Hemisphere). This means around 6 hours of light per day, to a minimum total of 500–550 hours of light during these three months (Nisen *et al.*, 1988). The duration of the day and night and, consequently, the total solar radiation depend on the geographical latitude and the time of the year (Table 1).

Other desirable climate parameters for these species would be soil temperature of > 14 °C and ambient relative humidity of 70–90% (Nisen *et al.*, 1988).



Plate 4
Protection against rain in regions of high rainfall



Plate 5
Tomato: widespread in Mediterranean greenhouses

TABLE 1
Values of maximum global solar radiation intensity (W/m²) predictable as a function of latitude (midday, Northern Hemisphere)

Latitude	Dec.	Mar.	June	Sept.
32°N	550	915	1 050	855
38°N	455	845	1 025	780
44°N	355	770	995	685

Nisen *et al.*, 1988

Obtaining the required climate conditions

The difficulty of increasing, at a reasonable cost, the natural radiation conditions (except in very sophisticated greenhouses and with high-value crops) makes it necessary to design and locate greenhouses to optimize the interception of solar radiation during the autumn and winter months. Therefore, the natural radiation conditions are the main limiting factor to consider when establishing greenhouses.

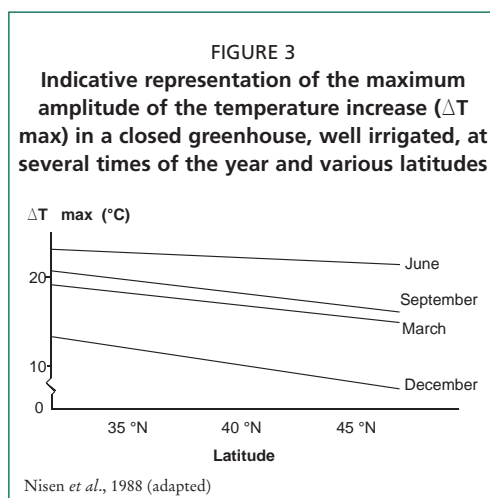
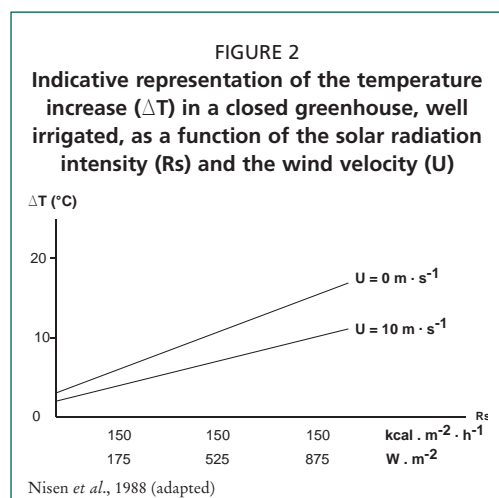
Given the parallelism between air and soil temperatures (even with less oscillation inside a greenhouse than in the open air), achieving a suitable ambient temperature also involves proper soil temperature values. FAO proposed a methodology for achieving the required climate conditions (Nisen *et al.*, 1988).

Protected cultivation in greenhouses or high tunnels causes the increase of daytime temperature (in relation to the outside) to very high values (Figure 2), depending on:

- characteristics of the cladding material;
- outside wind velocity;
- incident solar radiation;
- transpiration of the crop grown inside the greenhouse.

Night temperatures, on the other hand, only increase slightly in relation to the outside (2–4 °C at the most) and, in some cases, are lower (thermal inversion). The maximum temperature increase varies with latitude and, for each specific location, with the time of year as the solar radiation changes (Figure 3).

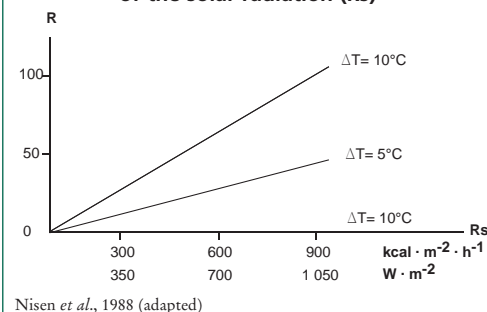
To increase low temperatures, the most common solution is to heat the greenhouse, but this is not always profitable. In some cases, an efficient isolation system can prevent temperature drop at night – as in the “lean-to greenhouse” in



China, where a curtain of canes and wood is manually placed over the greenhouse cover at sunset, then removed at sunrise. This solution prevents major temperature decreases at night, but is highly labour-intensive. To limit temperature excesses, the renewal of interior air by means of ventilation is the classic and most economic tool.

The hourly air renewal rate needed to keep the temperature gradient at a certain value, depending on maximum predictable solar radiation, can be very high (Figure 4) and impossible to achieve without mechanical ventilation.

FIGURE 4
Estimation of the hourly air exchange rate (R, in volumes per hour) in a well-irrigated greenhouse, to maintain the ambient warming at a given air ΔT value ($^{\circ}\text{C}$) with respect to the outside air as a function of the solar radiation (R_s)



Climate suitability

The fundamental requirements of those thermophilic horticultural species for which there is a high demand for out-of-season cultivation (tomato, pepper, melon, watermelon etc.) are as follows (Nisen *et al.*, 1988):

- Minimum global radiation of 8.5 MJ/m²/day (equivalent of 2.34 kWh/m²/day).
- Average ambient temperatures of 17–27 °C in coastal areas and 17°–22 °C in inland areas (far from the sea). This distinction is based on the fact that the daily thermal oscillations of inland areas (around 20 °C) are higher than those of coastal areas (10 °C)

It is not economically viable to actively control the microclimate in unsophisticated greenhouses, and minimum greenhouse temperatures are therefore very similar to those in the open air, especially when there are no heating systems. The maximum temperatures with passive normal ventilation can be around 10 °C higher than outside, involving an increase in the average temperatures of about 5 °C. In the light of these considerations, the thermal climate limits for protected cultivation without active climate control equipment are 12–22 °C in coastal areas and 12–17 °C in inland areas. Outside these limits, protected cultivation requires active climate controlling systems: heating, mechanical ventilation and cooling.

Figure 1 represents the climate diagram of Almería. Solar radiation in December is at its minimum. Temperatures are slightly below 12 °C (minimum threshold) in January, and heating is therefore necessary. With the exception of the summer (June, July, August and September), the remaining months present thermal conditions suitable for protected cultivation (12–22 °C) with efficient ventilation. In the summer, thermal excesses must be limited to cultivate inside greenhouses.

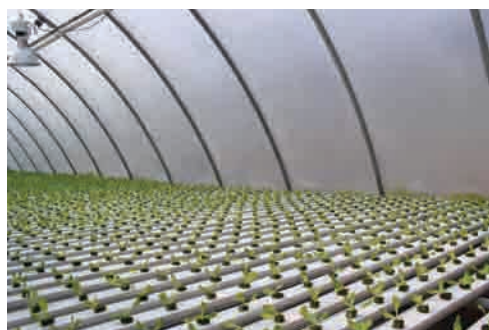


Plate 6

Lettuce greenhouse cultivation: species with lower thermal requirements prevail when cold

Obviously, the indicated method constitutes only a primary approach to evaluating the climate suitability of a region for the cultivation of thermophilic vegetable species. Similarly, it is possible to evaluate the climate suitability of a certain location for greenhouse cultivation of other less thermal-demanding species, such as lettuce and Chinese cabbage (Plate 6).

The use of screens instead of plastic films as covering material induces a minimal greenhouse effect, generating shading and windbreak effects. Screenhouses are an option for protected cultivation and are becoming more widespread in low-rainfall areas with very mild winter temperatures, and in highlands at medium latitudes during the summer.

GREENHOUSE LOCAL SITE

The specific selection of a greenhouse location must take into account a variety of factors (Castilla, 2007), described below.

Topography

In principle, the location must be flat in width direction, with a slope in the main axes between 0 and 0.5 percent, and never over 1–2 percent, as this would require terracing. In some cases, however, a south-oriented inclined plot (in the Northern Hemisphere) may be acceptable if the chosen greenhouse type adapts well; in this case, mechanization is rare (such as on Spain's south coast, where low-cost greenhouses are common on the coastal slopes – Plate 7). Normally, on steep terrains, it is recommended to build several separate greenhouses with axes parallel to contour lines. Provisions must be made for the evacuation of rainfall water, and greenhouses should not be situated in hollow lands.



Plate 7

Coast of Granada (southern Spain): south-facing slopes with better solar radiation in autumn and winter

Microclimate

As with liquids, cold air moves downwards (as it is heavier than hot air) to the lower parts of the site, and stays there if there is no wind to carry it away. Therefore, it is essential that the local topography is suitable for effective drainage of cold air during calm nights. Frequently foggy areas should be avoided. Areas that are well illuminated and free from shadows (hills, buildings) are preferred.

Harsh weather conditions

Sites should be protected from cold winds (usually from the north in the Northern Hemisphere), using windbreaks or taking advantage of the topography. If snow is to be expected, greenhouses must be positioned sufficiently far from trees or other obstacles to the wind, since snow may accumulate around such obstacles.

Irrigation

It should be emphasized that the availability of water (in sufficient quantity and of good quality) is an essential requirement for greenhouse growing of high added value crops. Many areas have been abandoned due to the lack of water in sufficient quantities and of acceptable quality (salinity) in the Mediterranean Basin.

Drainage

The drainage conditions must be good, especially in regions of high rainfall. Places with a high water table must be avoided.

Soil characteristics

Whether cultivation is directly in the soil or in pots or containers, the soil must have properties appropriate for horticultural crops.

Pollution

For greenhouses located in urban areas, air pollution conditions must be evaluated, not only in terms of incidence on the plants themselves, but also with regard to residues deposited on the greenhouse, which can limit solar radiation (e.g. dust from factories) or damage the greenhouse cladding material.

Availability of space

Space may be required for future enlargement, auxiliary facilities (e.g. water basins for collection of rainfall water or storage of irrigation water) and buildings (e.g. handling, stores, offices).

Availability of labour

If local labour is not available, it is necessary to consider the costs inherent in acquiring labour.

Infrastructures

Proximity to transport networks (e.g. roads, railway), access to communication systems (e.g. telephone, internet) and availability of energy (e.g. gas, electricity) must all be considered.

Orientation

The position must be chosen to avoid shadows from hills or neighbouring buildings. It is necessary to adapt the shape and slope of the roof to dominant winds, while maintaining the objective of maximum light in the greenhouse.

GAP recommendations

Site selection:

- Production costs and yield quality are key factors when choosing the greenhouse site; they depend mainly on climate conditions determining the greenhouse microclimate.
- Transportation costs are a crucial factor, although greenhouse production has expanded to areas far from destination markets, thanks to improvements in communications and logistics.

Climate conditions:

Profitable and sustainable cultivation of the target crop requires strict selection of the region, on the basis of its climate conditions and the requirements of the selected horticultural crop, noting the following considerations:

- Solar radiation (and its year-round availability) and air temperature are the two main climate parameters to evaluate.
- In cold and mild winter climate areas, the greenhouse effect prevails and the main objective is temperature increase.
- In tropical and subtropical areas, the windbreak effect (protection from strong winds), the umbrella effect (protection from heavy rains) and the shading effect (protection from high radiation) prevail.
- In arid and semi-arid regions, the oasis effect (raising air humidity and limiting high temperatures in a well-watered crop) prevails: there is increasingly widespread use of screens instead of plastic films as cladding material.

Market identification, establishment of distance, production planning (vegetables, fruits or ornamentals), knowledge of strategy to meet climate requirements:

- The best site offers the best climate conditions with the lowest production costs, with special attention to the availability of labour and inputs (water quality, electricity, communications etc.), and the distance to markets (transportation costs).
- Markets demand year-round production (not always possible in the Mediterranean area in a passive climate control greenhouse).
- There are two strategies for meeting climate requirements: invest in high-tech greenhouses which avoid strong dependence on the outdoor climate; or grow in two or more locations with complementary harvesting periods, enabling a continuous and coordinated year-round supply to markets.

GAP recommendations (cont.)**Region selection on the basis of climate conditions and crop requirements:**

- Solar radiation is the first climate parameter to be evaluated, in particular year-round availability.
- Other important parameters are soil temperature (linked to air temperature) and, to a lesser extent, wind, rainfall and air composition (humidity and CO₂).
- The most commonly grown species in Mediterranean greenhouses are vegetables with medium thermal requirements (tomato, pepper, cucumber, melon, watermelon, marrow, green bean, eggplant etc.).
- Suitable species are warm season crops, adapted to average ambient temperatures ranging from 17 to 28 °C, and with limits of 12 °C (minimum) and 32 °C (maximum) (Nisen *et al.*, 1988). They are sensitive to the cold and suffer irreversible damage with frosts.
- Minimum daily radiation requirements of these species are estimated at around 6 hours of light per day, totalling a minimum of 500–550 hours of light during the 3 shortest months of the year (November, December and January in the Northern Hemisphere; May, June and July in the Southern Hemisphere).
- Unless there is an imperious need (and very high selling prices), greenhouse production is not recommended in geographical areas with unsuitable climate conditions requiring notable and expensive artificial climate control.
- Given the impossibility of increasing, at a reasonable cost, natural radiation conditions (except in very sophisticated greenhouses and with high-value crops), greenhouse design and location must optimize the interception of solar radiation during autumn and winter.
- To raise low temperatures, the most common solution is to heat the greenhouse, but this is not always profitable. In some cases, a highly isolating system can avoid temperature drop at night (e.g. “lean-to greenhouses” in China).
- To avoid excessively high temperatures, the traditional and most economically viable method is the renewal of interior air by means of ventilation.
- Other important parameters for climate suitability are soil temperature (linked to air temperature) and to a lesser degree, wind, rainfall and air composition (humidity and carbon dioxide, CO₂). There are some differences between air temperature and plant temperature and also between parts of the plant, especially during daytime, depending on the radiation intercepted, the water transpiration and the air movement. The root temperature is assumed to be the same as the soil temperature.

CONCLUSIONS

Site selection is crucial for profitable and sustainable greenhouse production. The climate influences the type and level of greenhouse technology (structure and internal equipment for climate control) and subsequent crop production conditions, which in turn influence product cost and quality. The distance to markets, especially in export-focused production, can be a limiting factor for profitable greenhouse cultivation. An economic compromise between the investment costs of the greenhouses and equipment and their agricultural performance is necessary to produce proper quality commodities at a competitive level.

Greenhouse site selection – Summary of considerations

Topography: flat in width direction; main axes slope of 0–0.5 percent (never > 1–2 percent, which would need terracing)

Microclimate: not frequently fogged areas, no shadows from hills etc.

Protection from cold wind: windbreaks

Irrigation water: adequate quality

Soil characteristics

Flooded areas: avoid; build drainage if necessary

Air pollution: especially near cities

Expansion: space for future greenhouse or auxiliary buildings

Labour availability

Communications network

Orientation: prioritize light interception in winter, adapted if possible to dominant winds

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3. Greenhouse design and covering materials

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INTRODUCTION

The energy crisis in the 1970s may be considered the main reason for the development of Mediterranean horticulture. As energy prices rose, the greenhouse surface area remained stable or decreased in countries with low winter temperatures, while it increased significantly in areas where heating requirements were much lower. Mediterranean horticulture benefited from the availability of abundant autumn and winter light and from the mild winter conditions resulting from the proximity of the growing areas to the sea (Castilla and Hernández, 2005). The energy scenario led to the establishment of two distinct production models (Figure 1):

- Cold countries adopted advanced greenhouse technology, increased light transmission, saved energy for heating and optimized all production means to achieve maximum yield; they used glass as covering material.
- Southern or Mediterranean greenhouses adapted to the local conditions, with moderate investments and little (if any) climate control system besides natural ventilation; this produced suboptimal conditions for plant production and as a consequence lower yields than high-tech greenhouses; they used mostly plastic film as covering material (Castilla, 2005).

This chapter discusses the most relevant issues related to greenhouse design and covering materials for good agricultural practices (GAP) in Mediterranean areas. Four main areas are dealt with: greenhouse types, plastic films as covering materials, insect-proof screens and greenhouse natural ventilation.

FIGURE 1

Two greenhouse production models:**High technology typical of cold regions and low-medium technology typical of the Mediterranean****Option 1****ACTIVE CLIMATE CONTROL**

- High yields
- Good quality almost year round
- Regular production
- High costs

**Option 2****PASSIVE CLIMATE CONTROL**

- Limited yields
- Good quality in limited periods
- Irregular production
- Low costs

**MAIN GREENHOUSE TYPES IN THE MEDITERRANEAN BASIN****Local-type greenhouses**

These greenhouse types are normally very low-cost structures with little climate control besides natural ventilation; they are built with local materials (i.e. wood) and covered with polyethylene plastic film. The *parral*-type greenhouse is probably the most widely used in terms of surface area. In Almería (Spain) alone it covers approximately 27 000 ha (EFSA, 2009). The *parral* greenhouse is made of a vertical structure of rigid pillars (wood or steel) on which a double grid of wire is placed to attach the plastic film. As in other parts of the Mediterranean,

the cost of materials obtained locally and the availability of installation expertise have been fundamental for greenhouse expansion.

**Plate 1**

*Flat-roof greenhouses in Almería
(southern Spain)*

Local-type greenhouses require a relatively low level of investment, making them suitable for farms operated by small growers. However, there are significant design-associated problems, such as lack of tightness, low radiation transmission in winter and, more importantly, lack of good natural ventilation as a result of:

- low ventilator surface area, due to a poor combination of side and roof ventilation and to the construction of excessively small roof vents, resulting from the grower's fear of sudden strong winds that may damage the ventilators.
- inefficient ventilator designs – for roof ventilation, flap ventilation is always preferable to rolling ventilators as it provides higher ventilator rates (almost three times greater airflow according to Pérez-Parra *et al.* [2004]).
- use of low porosity insect screens – insect-proof screens strongly reduce the air exchange rate.

Good agricultural practices require good ventilation and light transmission. The lack of good ventilation in most local-type greenhouses can be compensated for by improved design of the ventilation systems. Light transmission depends on the properties of the covering material and the number of opaque supporting members, as well as the greenhouse geometry and orientation. In terms of roof slope, computer simulations show that during the winter, increasing the roof slope from 11 to 45° can increase daily light transmission by nearly 10 percent, since losses due to reflection are reduced. In practice, it is more useful to find a compromise between good light transmission and construction costs, and most new greenhouses have a roof slope of 25–30°.

With regard to greenhouse orientation, there are two main factors that have to be balanced before choosing the best solution: light transmission and ventilation.

At Mediterranean latitudes (37°N), for greenhouses with a 10° roof slope, east to west (E–W) orientation has better transmission than north to south (N–S) during winter, while it has lower transmission in the summer; however, the differences are small (Figure 3a). For greenhouses with a 30° roof slope, the E–W greenhouse transmits approximately 13 percent more than the N–S greenhouse during the winter period (Figure 3b).

Therefore, in terms of light transmission, it is recommended to build the greenhouse with an E–W orientation. Nevertheless, light uniformity is better in N–S greenhouses since the gutter and ridge shadows change their position during the day as the sun moves. In some Mediterranean areas, greenhouses are E–W oriented, but the crop rows are N–S for greater crop uniformity.

With regard to ventilation, it is advisable to build the roof ventilators perpendicular to the prevailing winds to enhance the air exchange.

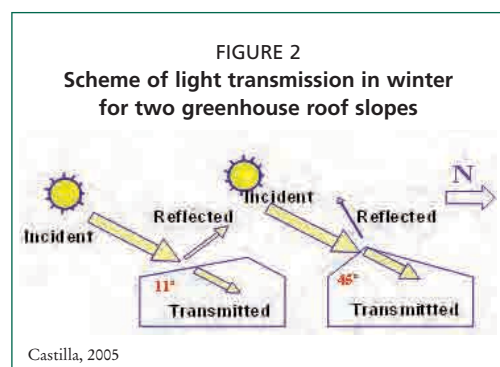
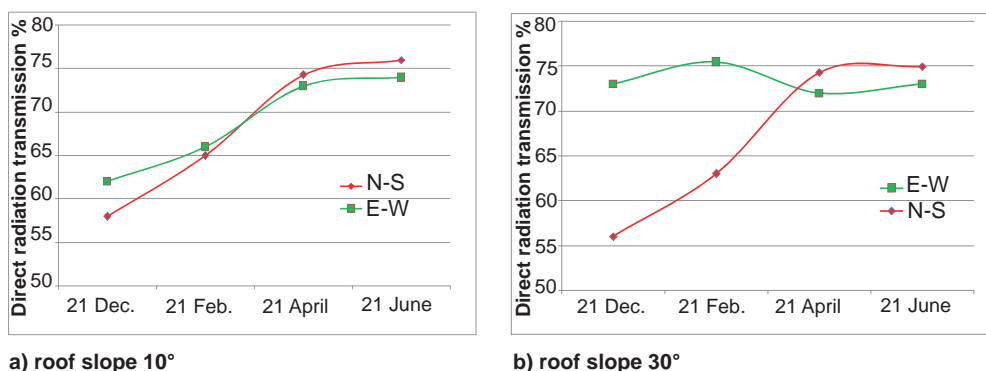


FIGURE 3
Direct radiation transmission for greenhouses with the main axis north-south and east-west,
latitude 37 °north



Castilla, 2005

Plastic-covered industrial-type greenhouses

A large number of different greenhouse structures may be included in this group (pitched roof multi-span, asymmetric multi-span, saw-tooth, curved roof multi-span etc.). The arch-shaped multi-span system prevails among the industrial types, mostly clad with plastic film or, in some cases, with rigid or semi-rigid materials (preferably polycarbonate). The roof is often covered with plastic film, while the side and front walls are covered with semi-rigid plastics. These arch-shaped multi-span structures are normally made of galvanized steel and are preferred by the ornamental growers and nurseries. Multi-span structures are tighter than *parral*-type greenhouses and easier to equip with cooling, heating and/or computer control; such structures are very common in Israel.

In general, this group includes greenhouses with more efficient ventilation systems: the roof vents are usually larger than in the handmade greenhouses with



Plate 2

Arch-shaped multi-span greenhouses with single and double roof ventilators

at least one roof vent per span (double roof vents per span can also be found). In some cases, these structures may also have combined roof and sidewall ventilation. Sometimes roof ventilators are in an alternating mode facing one direction and the opposite direction, but there is no scientific evidence that this arrangement adds any advantage.

While arch-shaped multi-span greenhouses have many advantages, they are not free from problems. Condensation can occur in the upper inner part of the roof, resulting in dripping in humid and cold weather, usually during the early hours of the day. Attempts have been made to solve this problem by increasing the roof slope with pointed arches instead of circular, but this has not entirely eliminated the condensation.

Glasshouses

Glasshouses are the most commonly found greenhouse structures in cold parts of the Northern Hemisphere. They are usually built in very large compartments in order to lower cost per unit area, improve efficiency and reduce heat loss through the sidewalls; in the Netherlands the average glasshouse area was 1.5 ha in 2003 (Bunschoten and Pierik, 2003). They usually have only roof ventilators, which may be discontinuous (e.g. Venlo type, one-side mounted windows) or continuous. The relation between the ventilator area and the greenhouse covered area is often around 25 percent, which is close to the ASABE standards (ASABE, 1999).

The glasshouse area in southern European countries is limited, mainly because of the high investment costs. Glasshouses occupy less than 1 percent of the total greenhouse area in countries such as Spain. If glasshouses are to be constructed in climate areas warmer than northern Europe, ventilation must be improved. The combination of roof and sidewall ventilation ensures higher ventilation rates, both in windy conditions (Kacira *et al.*, 2004a) and in low or zero wind conditions with buoyancy-driven natural ventilation (Baeza *et al.*, 2009).



Plate 3
Venlo-type glasshouses

Greenhouse types – Conclusions and GAP recommendations

- Enhancing winter light transmission is an important good agricultural practice in Mediterranean areas: greenhouses must have a minimum roof slope of 25–30°.
- Local-type greenhouses, if properly designed, are suitable for mild climate areas. Their main advantage is their low investment cost; their principal disadvantage is the lack of climate control (mainly lack of ventilation).
- Avoid low roof slope greenhouses for better light transmission.
- If ventilation is of greater concern than light transmission, orient the greenhouse so that the vents are open towards the prevailing winds.
- Choose E–W orientation if there is no conflict with ventilation.
- Crop rows must be N–S for optimum light uniformity.
- Industrial-type plastic-covered greenhouses can modulate unfavourable external conditions. While recommended over the local-type greenhouses, their cost-benefit analysis could be worse than for local-type greenhouses in the short term.
- Glasshouses are excellent greenhouse structures, but they are not popular in southern European countries, mainly because of the high investment costs.

PLASTIC FILMS AS GREENHOUSE COVERING MATERIAL

A covering material is chosen for its optical and mechanical properties and on the basis of climate and location (Waaijenberg and Sonneveld, 2004). Good agricultural practices dictate that greenhouse plastic should have maximum solar transmission (so dust washes away easily and does not stick) and be opaque to long-wave radiation to reduce heat loss at night.

Greenhouse films are composed of polymers and additives. Polymers are the basic component, while additives provide a variety of different properties including infrared absorption/reflection and light diffusion. Greenhouse cladding films range in thickness from 80 to 200 µm. Film width is up to 20 m. Single layer or multilayer (typically three-layer) films are widely used in commercial production, but multilayer films are preferred as they combine the positive properties of their individual components (e.g. good mechanical resistance and good light transmission). The life span of greenhouse films has increased from 9 months during the 1950s to approximately 45 months today. Weathering depends on the photo-additives incorporated in the film as well as on the geographic location and the exposure of the film to pesticide treatments (Cepla, 2006).

Polymers and additives

Polymers are large molecules formed by the association of smaller units called monomers. The most common polymers used in horticulture are low density polyethylene (LDPE), ethylene vinyl acetate (EVA) and ethylene butyl acrylate

(EBA). These three polymers cover more than 80 percent of the world market. Other materials are also popular, such as PVC in Japan or linear low density polyethylene (LLDP) in the rest of the world. In comparison with glass, a property common to all plastic materials is their low density and therefore low weight (Table 1).

The low density and thickness of plastic materials is a great advantage in horticulture since it facilitates transportation, handling and installation. For example, 1 m² of LDPE film 200 µm thick weighs approximately 184 g; the same film made of PVC weighs about 260 g; while a glass pane 4 mm thick weighs 10 kg. The light weight and flexibility of the covering material allows a significant reduction in the size and number of the supporting members, making the greenhouse frame lighter compared with the glasshouse frame, and thus much cheaper.

Additives are an essential part of the covering materials. They are dispersed between the chains of polymer molecules without interacting chemically. Additives are used to facilitate the manufacturing of the film as well as to improve its performance under field conditions; the type and quantity of additive depends on which properties of the covering material need improving.

The two most common additives in horticulture are UV (ultraviolet) stabilizer additives and IR (infrared) absorbing additives. UV stabilizers absorb UV radiation or protect the polymer molecules. As a consequence, the film ages more slowly: indeed, the vast majority of plastic films in horticulture last more than one year and include UV stabilizer additives.

Good greenhouse film should block long-wave IR radiation (wavelength 0.7–4 µm) so as to reduce heat loss. So-called thermal films are particularly effective for increasing leaf temperature in passive, unheated greenhouses during clear nights. Polyethylene films are very transparent to long-wave IR radiation, therefore IR-absorbing additives are commonly used to improve the thermal properties of the films.

Properties of greenhouse plastic covering materials relevant to GAP

Clear films and diffusive films

In areas with clear skies and high solar radiation, direct radiation can cause leaf burning in greenhouse crops on warm days. New plastic films have been developed to increase the percentage of diffuse radiation in the greenhouse. Radiation is considered “diffuse” when it deviates more than 2.5° from the

TABLE 1
Density of different polymers used in horticulture

Material	Density (g/cm ³)
Low density polyethylene (LDPE)	0.915–0.930
Copolymer ethylene vinyl acetate (EVA)	0.920–0.930
Copolymer ethylene butyl acrylate (EBA)	0.920–0.930
Polyvinyl chloride (flexible) (PVC)	1.250–1.500
Polymethyl methacrylate (PMMA)	1.180
Polyester/Fibreglass	1.500–1.600
Glass	2.400

**Plate 4**

Covering greenhouse films: clear film (left); diffusive film (right)

**Plate 5**

Greenhouse covered with different plastic films

additives that increase electrical conductivity can be incorporated into the interior or on the surface of the film. Montero *et al.* (2001) reported that dirt accumulation reduced light transmission of a new PE plastic film by approximately 6 percent after 1 year of exposure in coastal Spain. EVA films are reported to lose more light transmission due to dust accumulation.

direct incident radiation. The percentage of diffuse radiation to global radiation is known as turbidity. Increased turbidity results in greater light uniformity and higher yields in Mediterranean countries (Castilla and Hernández, 2007; Cabrera *et al.*, 2009). Diffusive light also has positive effects in northern countries such as the Netherlands. Hemming *et al.* (2008) compared the effect of diffusive glass against clear glass and concluded that more light was intercepted by the crop in diffuse treatment, especially by the intermediate leaf layers; thus assimilation was higher and cucumber production increased by approximately 8 percent.

Anti-dust films

Most polymers are poor electricity conductors, particularly prone to the accumulation of static electricity when two surfaces are rubbed against each other or when there is friction caused by the wind. As a consequence, most plastics attract dust. To reduce static electricity, some

**Plate 6**

Anti-dripping film (right side)

Anti-drip films

Water vapour condenses on the cold inner cover surface forming small droplets of liquid water. This has negative consequences on light transmission; some condensation studies have reported PAR (photosynthetically active radiation) transmission losses close to 20 percent for incident radiation angles bigger than 15°. This loss in light transmission varies with drop size: large drops reduce transmission less than small drops due to the different

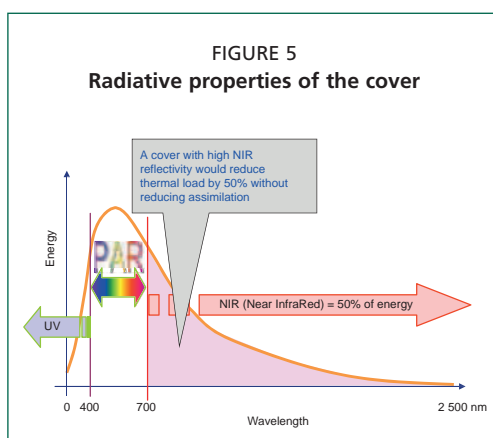
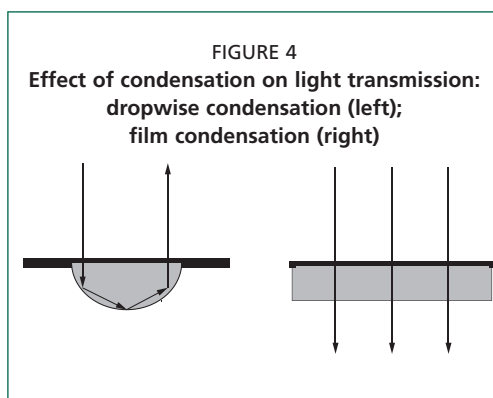
contact angle of the drop with the plastic (Castilla, 2005). Moreover, condensation can fall onto the crop fostering development of fungal diseases. Anti-drip additives modify the surface tension of water, eliminate droplets and form instead a continuous thin layer of water (Figure 4).

There are several methods for producing a continuous layer of condensed water, such as treatment of the film surface or oxidation of the polymer surface, but the most efficient method for agricultural films is the incorporation of additives during the manufacturing process. However, such additives migrate towards the plastic surface getting washed away by rain or condensation, and anti-drip properties are usually lost before the end of the plastic's life span. One solution is to use multilayer plastics where one of the central layers is used as a reservoir of anti-drip additives which continuously replace the additives lost through washing.

NIR-blocking plastic materials

Only about half of the energy that enters a greenhouse as sun radiation is in the wavelength range useful for photosynthesis (PAR: photosynthetically active radiation). Nearly all the remaining energy fraction is in the near infrared range (NIR): it warms the greenhouse and crop and contributes to transpiration, none of which is necessarily always desirable (Figure 5).

Some new plastic film prototypes contain NIR-reflecting pigments with several concentrations. A significant reduction of the sun radiation energy content in the NIR range is thus possible without much reduction in the PAR range. The effectiveness of NIR films on the reduction of greenhouse air and crop temperatures and their effects on crop yield and quality depends on a number of factors, such as the amount of NIR filtered by the film, the ventilation capacity of the greenhouse, the crop density and the canopy transpiration. The desk study of Hemming *et al.* (2006) showed that under Dutch conditions, mean air temperature in a Venlo-type greenhouse could be reduced by about 1 °C during the summer months, but the NIR film increased energy consumption for heating in the winter months. Field tests conducted in southern Spain produced

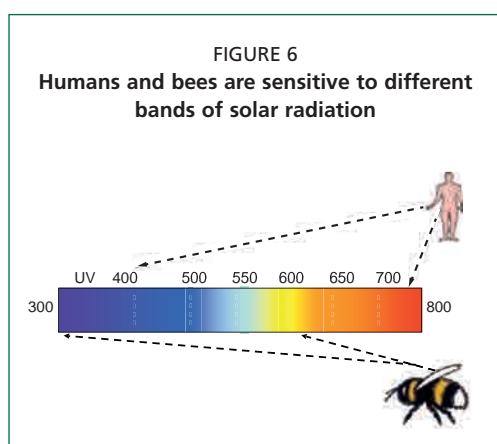


more optimistic results – temperature reductions of up to 4 °C during summer months, and increased yield and quality of a pepper crop (García-Alonso *et al.*, 2006).

Three application methods are possible for commercially available NIR-selective filters: as permanent additives or coatings of the cover; as seasonal “whitewash”; and as movable screens. The combination of external climate conditions and type of greenhouse determines the most appropriate form of application in a given location. Some of these factors have been taken into account in the study by Kempkes *et al.* (2008), which quantifies the expected benefits in terms of inside climate. They show that year-round filtering of the NIR component of sun radiation is unlikely to increase productivity, even in mild winter climates, unless the reflected energy can be used.

Blocking UV radiation to limit harmful insect activity

The term “UV blocking” is applied to plastic films and nets made by various manufacturers with different capacities to absorb sunlight below 380 nm. The two most harmful insects for crop production in Mediterranean greenhouses are *Bemisia tabaci* (whitefly) and *Frankliniella occidentalis* (thrips), mainly because both are effective vectors for the transmission of virus diseases. The ability of these insects to move is associated with UV radiation; hence, by using plastic materials that absorb UV radiation, virus-disease transmission can be mitigated (González *et al.*, 2003). The subject is dealt with in more detail in the section on insect-proof screens.



However, reducing UV radiation also limits the role of beneficial insects used for pollination, such as *Apis mellifera* (bees) and *Bombus terrestris* (bumblebees). Field tests in the Mediterranean area show that insect pollination is not affected, provided that enough time is given to the beehives to get accustomed to the low UV levels within the greenhouse. It must also be pointed out that blocking UV-radiation may have detrimental effects on secondary metabolism, i.e. plant defences and micronutritional quality of products (subjects not discussed in this chapter).

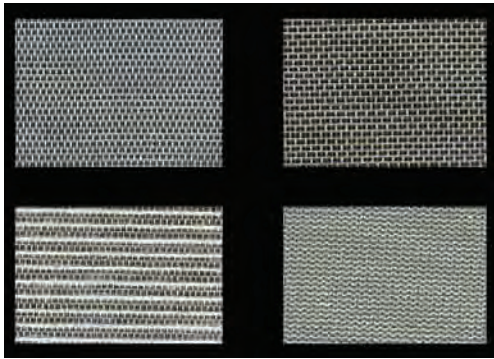
Plastic covering materials – GAP recommendations

- Multilayer rather than single-layer films are recommended since they allow addition of the positive properties of each of the components that form the film.
- Diffusive films are preferred over clear films because they improve light uniformity and increase light interception by the crop.
- EVA films on the outer surface of the cover are to be avoided in dusty areas due to higher losses in light transmission.
- Anti-drip films improve transmission and reduce dripping from the inner surface, but usually lose their anti-drip properties before the end of their life span.
- In Mediterranean climates, a permanent NIR filter may have useful applications during the summer, but could be detrimental during the winter.
- Movable screens or seasonal whitewashing with NIR filter have good potential; this technique is currently under investigation.
- UV-blocking films are a promising technique to reduce pest infestation, but their commercial availability is still limited.

INSECT-PROOF SCREENS FOR GOOD AGRICULTURAL PRACTICES

In the Mediterranean and southeastern Europe most greenhouses are equipped with ventilation openings to provide good microclimate conditions for plant growth. Unfortunately, these vents serve also as a major port of entry for pests and, as a consequence, growers are forced to cover the vents completely and permanently with fine mesh screens to prevent pest invasion. Since the pests can be very small (e.g. whiteflies and thrips), very fine mesh screens are required to prevent their entry; these screens impede ventilation and, in some cases, reduce light transmission (Bethke *et al.*, 1994; Klose and Tantau, 2004; Teitel, 2001). Moreover, the targeted insects are most abundant during the warm and hot seasons when effective ventilation is essential for avoiding stressful conditions for both crop plants and workers (Teitel, 2001).

Screens are characterized by their porosity (ratio between open area and total area), mesh size, thread dimension (diameter or thickness), texture (woven, knitted, woven/knitted), colour, light transmission/reflection and resistance to airflow. Most insect-proof screens have square or rectangular openings and are made of monofilament threads. They are generally characterized by the term “mesh”, which is the number of open spaces per inch in each direction, delineated by the threads (e.g. a 50-mesh screen has 50 spaces per inch in either the warp or the weft direction). Usually, screens are a product of weaving: a set of threads (the warp) stretched in a frame, or loom, are bound together to form a

**Plate 7**

Samples of insect proof screens

Top: simple geometries, round monofilament threads, rectangular holes

Bottom right: complex geometry, round monofilament threads, irregular hole shapes (areas hard to measure)

Bottom left: complex geometry, vertical threads round monofilament, horizontal threads some round monofilament, others with lashes

coherent fabric by means of other threads (the weft) introduced at right angles to the warp threads and passing in a determinate order over and under them. In Europe, screens are generally characterized by the number of spaces per centimetre in each direction (e.g. a 10*20 screen has 10 spaces per centimetre in one direction and 20 in the other direction). Nevertheless, there could still be difficulties in characterizing a screen with a complex weave (i.e. where the threads do not form openings of a simple rectangular or square shape or when the threads are not a round monofilament fibre with an easily measured diameter). For such screens, there is still no reliable method of documentation; they can only be characterized with laboratory tests relating pressure drop on the fabric as a function of upstream velocity.

Effect of insect-proof screens on ventilation

An important consideration when designing a screen installation is the effect that screen materials have on airflow through the openings. It has been well documented that screens increase the pressure drop on the openings, which results in reduced ventilation. It is also well known that the pressure drop on screens is mainly a function of screen porosity. For a woven screen made of a monofilament thread and with a simple texture, it is possible to calculate the porosity (ε) from the geometric dimensions of the screen:

$$\varepsilon = \frac{(l - d)(m - d)}{ml} \quad \text{Eq. 1}$$

where:

l and m are the distance between the centres of two adjacent weft and warp threads, respectively

d is the diameter of the threads

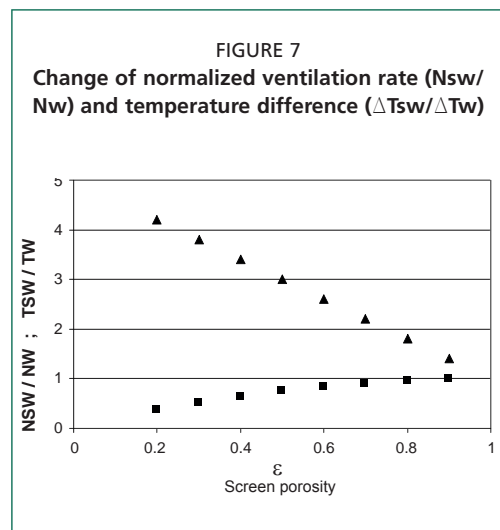
This porosity relates to an orthogonal projection of the screen. Teitel (2007), on the basis of data from literature, suggested the following correlation:

$$\Delta T_{sw} = \Delta T_w (5 - 4\varepsilon) \quad \text{Eq. 2}$$

to estimate the effect screens on the vents have on temperature difference between greenhouse and ambient air with screens (ΔT_{sw}) and without screens (ΔT_w). Nevertheless, it should be kept in mind that Equation 2 provides

only a rough estimate of ΔT_{sw} , since the relationship between the temperature difference with and without a screen is dependent on greenhouse type, crop, weather and the exact location where the inside air temperature was measured. The change of $\Delta T_{sw} / \Delta T_w$ with the porosity is shown in Figure 7: as the value of porosity increases, the ventilation rate increases and the inside/outside temperature difference decreases.

From the study conducted by Pérez-Parra *et al.* (2004), it can be deduced that an anti-thrips screen can reduce ventilation by approximately 60–70 percent while an anti-aphid screen can reduce it by 40 percent.



In recent years, methods have been developed to improve the unfavourable conditions in the greenhouse due to insect screens:

- Incorporation of optical or electrical insect deterrents with insect screen, enabling growers to use low mesh screens while maintaining a high level of protection from pests.
- Removal of insect screens from vents when the risk of pest invasion is low.
- Maximization of screened area.

Photo-selective screens, colour effects and other modifications

There are two possible explanations for the mechanism by which photo-selective screens provide protection against arthropod pests:

- The light inside the greenhouse contains less UV light and therefore becomes “invisible” to the pest. There are reports of thrips and whiteflies preferring to move into UV-containing environments (Antignus *et al.*, 2001; Costa *et al.*, 2002; Doukas and Payne, 2007).
- Higher levels of reflected sunlight deter pest landing. Reports indicate that thrips are repelled by high UV reflectance (Matteson *et al.*, 1992; Vernon and Gillespie, 1990). Furthermore, total light reflection by aluminium mulches and aluminium-coloured screens also reduces pest infestations in both open fields and protected crops (Greer and Dole, 2003).

In recent years crops have been grown under coloured nets to promote beneficial physiological responses (Shahak *et al.*, 2008). Nets used are yellow or blue, colours known to attract whiteflies and thrips, respectively. The risk for pest infestation under these nets is equal to or lower than the risk under black nets.

While pests prefer landing on the coloured nets, they remain there for a long time; this form of arrestment response (Bukovinszky *et al.*, 2005) makes the pests less likely to infest the plants underneath these nets. Adding “arrestment colours” to insect screens is likely to reduce the risk of pest invasion in the greenhouse.

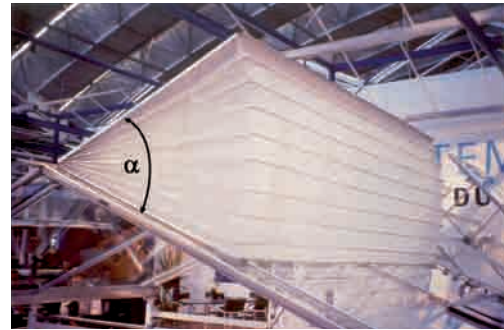
A promising new electrostatic insect-proof screen (electric dipolar screen) was developed by Tanaka *et al.* (2008). This screen prevented all adult whiteflies from passing through sparse screens with spaces of up to 30 mm between the wires. Tomato plants grown under the electrostatic screen had no whitefly infestation, while there were heavy infestations of plants under a similar uncharged screen.

Removing insect screen from vents when the risk of pest invasion is low

Optimal climatic conditions in the greenhouse are often maintained by closing and opening windows and vents. However, insect screens covering windows and vents are not regulated in response to changes in the risk of invasion by pests. Greenhouse ventilation is likely to be improved if ventilation openings are uncovered when there is no risk of pest invasion (Ben-Yakir *et al.*, 2008). In the fall, when the whitefly population peaks, over 97 percent of whiteflies entered the greenhouse between 7.00 and 13.00 hours (Teitel *et al.*, 2005). Thus, the risk of whitefly entering greenhouses in the afternoon and at night is negligible. The flight of onion thrips and western flower thrips was studied using sticky pole traps and similar traps mounted on wind vanes. For most of the year, about 85 percent of the thrips were caught in the morning and 10 percent at dusk (Ben-Yakir and Chen, 2008). Mateus *et al.* (1996) also reported that *F. occidentalis* in a pepper greenhouse had two daily flight peaks: one in the morning and one in the afternoon. Flight time was correlated with periods of low wind speed and thrips were seldom caught with wind > 10 km/h. It has been reported that thrips in the genus *Frankliniella* are deterred from taking off when wind speed exceeds 9 km/h (Lewis, 1997). Both whiteflies and thrips are not likely to enter protected crops during the hot and windy afternoon hours or at night. Therefore, insect screens may be removed from vents during those times. Nevertheless there is no general agreement between experts on the convenience of removing insect screens, so at present it cannot be considered a general GAP.

Maximizing the screened area

One method for increasing ventilation in multi-span greenhouses with roof openings on which screens are mounted is to increase the maximum angle at which the flap can be opened. Another option is to fit the frames of the openings with pre-formed concertina-shaped screens that unfold as the ventilators open and then fold up again when they close (Plate 8). Teitel *et al.* (2008) have shown that a concertina-shaped screen allows higher airflow (an increase of about 25%) when compared with a flat screen under similar pressure drops across the screen. Recent computational fluid dynamics (CFD) simulations, carried out by Teitel (unpublished data) suggest that concertina-shaped screens may allow much higher

**Plate 8**

Concertina-shaped screens installed in the roof openings of a Venlo greenhouse

ventilation rates (depending on the ratio between the concertina and flat screen area).

In addition to the effects on insect penetration and the ventilation rate, the screens reduce light transmission into the greenhouse by creating strips of shadow on the crop when they are installed on roof openings. In dusty regions the shadow effect may worsen with time due to the accumulation of dust on the screens. Klose and Tantau (2004) found that although screens with the largest distance between adjacent threads had the highest light transmission, screens with the smallest distance did not necessarily have the lowest. Hence, they concluded that light transmission was influenced by additional parameters, such as the structure of the threads and, of course, accumulation of dirt.

Insect-proof screens – GAP recommendations

- Insect-proof screens produce a major reduction in ventilation; it is estimated that an anti-thrips screen can reduce ventilation by 60–70 percent while an anti-aphid screen can reduce it by 40 percent.
- Ventilation reduction can be mitigated by increasing the ventilation surface and by increasing the screen area as in concertina-shaped screens.
- Screens with a smaller thread diameter are preferred as they are more porous and ventilate better.
- Photo-selective screens provide extra protection against pests. Moreover, adding “arrestment colours” (e.g. blue and yellow) is likely to reduce the risk of pest invasion in the greenhouse.

TRENDS IN NATURAL VENTILATION

Proper ventilation performance is crucial for greenhouses in both humid winter climates and hot summer conditions. The ventilation process contributes to optimal control of air temperature, humidity and concentration of gases within the greenhouse. Thus, photosynthetic and transpiration activities of plants are regulated properly and crop quality is improved. Given the advantages – low maintenance, low operational costs and reduced noise – natural ventilation is used by the great majority of growers in the Mediterranean area since it is the most inexpensive way to regulate greenhouse internal microclimate area. However, control of airflow with natural ventilation is limited. Therefore, it is necessary to analyse natural ventilation properly and increase ventilation efficiency.

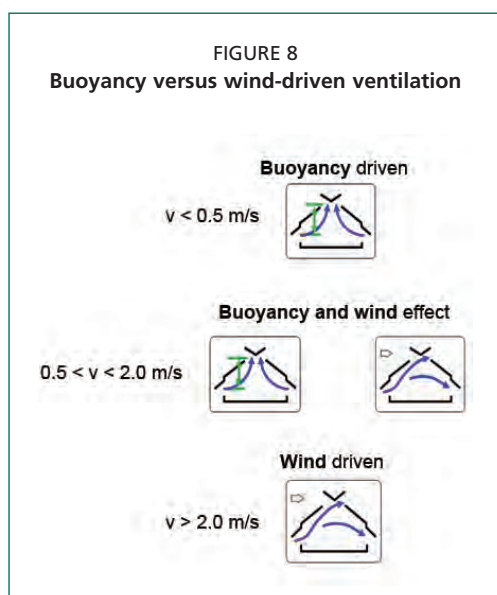
The driving force for natural ventilation is the pressure difference across the ventilation openings caused by wind and/or thermal effects.

Wind-driven ventilation

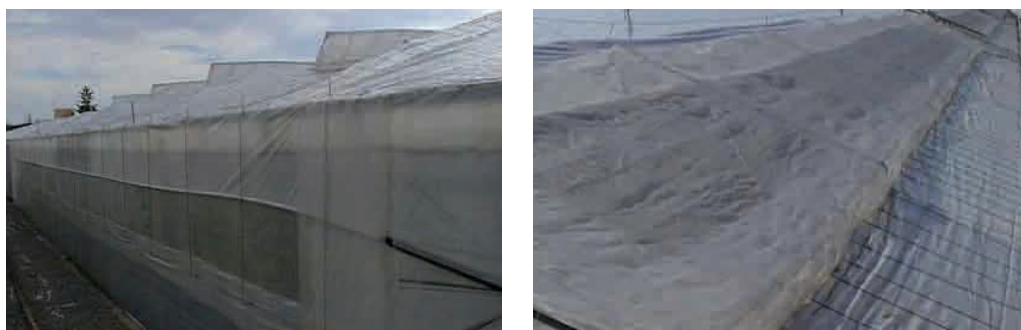
When the wind blows around a greenhouse, the wind field generates pressure distribution through the greenhouse. Moreover, wind has a fluctuating character that creates a fluctuating pressure difference over the openings; the mean difference in pressure and the fluctuating pressure difference are responsible for the airflow through the greenhouse ventilators (Bot, 1983; de Jong, 1990). There are claims that air exchange is proportional to outside wind velocity.

Thermally driven ventilation

Under calm conditions, buoyancy forces (differences between inside and outside air densities) are the driving mechanism for ventilation, but the effect of thermal buoyancy on ventilation is of fundamental interest when there is almost no wind (Baeza *et al.*, 2009). It has been reported that winds over 2 m/s dominate the ventilation process, making the effect of air temperature difference negligible (Bot, 1983; Papadakis *et al.*, 1996; Mistriotis *et al.*, 1997a). Buoyancy-driven ventilation is more important when wind speeds are below 0.5 m/s (Baeza *et al.*, 2009). Generally speaking, for intermediate and higher wind speeds, where $0.5 \text{ m/s} < u < 2.5 \text{ m/s}$, ventilation is driven mostly by wind effect and with some influence of buoyancy (Mistriotis *et al.*, 1997a) (Figure 8).



Natural ventilation can be achieved by opening windows at the top of the

**Plate 9**

Flap ventilators on the roof and rolling ventilators on the side wall (left)

Rolling ventilators on the roof (right)

greenhouse and/or at the sidewalls. The number and size of the windows and the mechanisms for window opening vary, with many different arrangements used in glasshouses and plastic-covered houses. Ridge openings can be classified as “continuous” or “non-continuous” and they are usually on both sides of the ridge, although hoses with openings on one side only are also constructed. Roof vents are either fixed or fully automatic (movable roof vents). A fixed overlapping vent on a gable ridge provides ventilation while preventing penetration of rain and hail. Movable roof vents may be formed by: film roll-up from gutter to ridge; ridge-hinged arched vents; vertical openings at the centre of the arch running the entire length of the roof; vertical roof openings starting at the gutters and extending to a height of about 1 m; or vertical openings at the centre of the arched roof running the entire length of the roof. The position and hinging of the vent at the ridge are the basis of a better evacuation of the hot and humid air which builds up at the top of the greenhouse. In Venlo greenhouses, the ventilators in most of the houses are hinged from the ridge and extend halfway to the gutter or as far as the gutter. The idea is to provide a large opening area especially in warm and humid areas. Recent greenhouse designs provide retractable roofs.

Side ventilation is usually achieved by rolling up curtains with a central mechanism operated manually or by an electric motor. Mechanisms that open the side vents from bottom to top (or vice versa, although less common) are available. Side openings with flaps hinged from the top are also used; however, they are more common in glasshouses than in plastic-covered houses. Flap ventilators are more efficient than rolling ventilators, particularly under moderate wind conditions.

Airflow characteristics under wind-driven ventilation

The latest advances in ventilation are based on numerical models, using computational fluid dynamics (CFD) to solve the governing equations. By using CFD models it is possible to obtain detailed vector fields of air velocity in and around the greenhouse, or precise fields of temperature, humidity or other variables relevant to greenhouse climate studies.

In order to better understand greenhouse ventilation, leeward and windward ventilation are examined in detail below. Windward ventilation is preferred to leeward ventilation for greenhouses located in warm areas, since windward ventilation clearly increases the ventilation rate (Pérez-Parra, 2002). Nevertheless, the internal climate is generally less uniform with windward ventilation.

Windward ventilation

The external air is “captured” by the vent opening of the first span. This results in an internal flow with the same direction as the external air. The first windward roof ventilator has the most significant effect on the intensity of air exchange and internal airflow (Baeza, 2007).

Leeward ventilation

The external wind follows the windward roof of the first span and accelerates along the roof. The external flow separates from the greenhouse structure at the ridge of the first windward span and creates an area of low speed above subsequent spans. Greenhouse air exits the greenhouse through the first roof ventilator, creating an internal flow which is opposite the external flow. As for windward ventilation, the first ventilator plays the leading role in the air exchange process (Flores, 2010).

This is the general outline of the air pattern for windward and leeward ventilation, but in very wide greenhouses the internal airflow may be different. Mistriotis *et al.* (1997b) and Reichrath and Davies (2001) have detected the occurrence of a dead zone with low velocity at approximately 60 percent of the total glasshouse length for a very large Venlo-type greenhouse (60 spans) under similar pure leeward ventilation conditions. Similarly, windward ventilation in wide greenhouses produces two clearly differentiated circulation areas. The zone where both circulation cells meet is a dead zone with low air movement and high temperature. The general recommendation is, whenever possible, to limit greenhouse width to approximately 50 m (Baeza, 2007) and to leave a separation between adjacent greenhouses to allow hot air to escape.

Sidewall ventilation

Sidewall ventilation is similar to windward roof ventilation with respect to the airflow pattern, since for sidewall ventilation the external air also enters the greenhouse through the windward side and passes along the greenhouse width. Kacira *et al.* (2004a) conducted CFD simulations to investigate the effect of side vents in relation to the span number of a gothic greenhouse with a continuous roof vent on the leeward side of each ridge. Compared with roof ventilation only, it was found that when both sides were fully open the ventilation rate increased strongly. The study showed that the maximum greenhouse ventilation rate was achieved when both side and roof vents were used for ventilation. Without buoyancy effect in the computations, the ventilation rate increased linearly with the external wind speed. The ratio of the opening of the ventilator area to the greenhouse

floor area (9.6%) was found to be small compared with the recommended ratios of 15–25 percent. The results showed that a significant reduction in ventilation rate was determined as the number of spans was increased (from 6 to 24) and an exponential decay described the relationship between the ventilation rate and the number of spans.

Sidewall ventilation may help reduce the area of the dead zone with high temperatures typical of wide greenhouses. However, side ventilation is not accepted by many growers who are reluctant to open the sidewall and roof ventilators in the windward direction, as they want to protect their crops and greenhouse frames from potential wind damage. For this reason, side deflectors are currently being put into practice (Baeza, 2007) and simple mechanisms to protect ventilators against wind gusts are becoming popular in Mediterranean countries.

Suggestions to improve natural ventilation

Use of deflectors

As pointed out by Sase (2006), in many types of ventilator the incoming air mainly follows the inner surface of the roof and creates a crossflow above the crop without mixing with the air in the crop area. To avoid this problem, the use of screens or deflectors to redirect the air stream is recommended. Nielsen (2002) offered a method to direct the passing airflow at the hinged ridge vents into the crop space (Figure 9): using a 1-m high vertical screen mounted to the ridge, improvements were achieved in the air exchange in the plant zone of about 50 percent on average.

Kacira *et al.* (2004b) evaluated the optimization of the traditional vent configuration for a two-span glasshouse for better air renewal especially in the plant canopy zone. The study was based on three-dimensional numerical

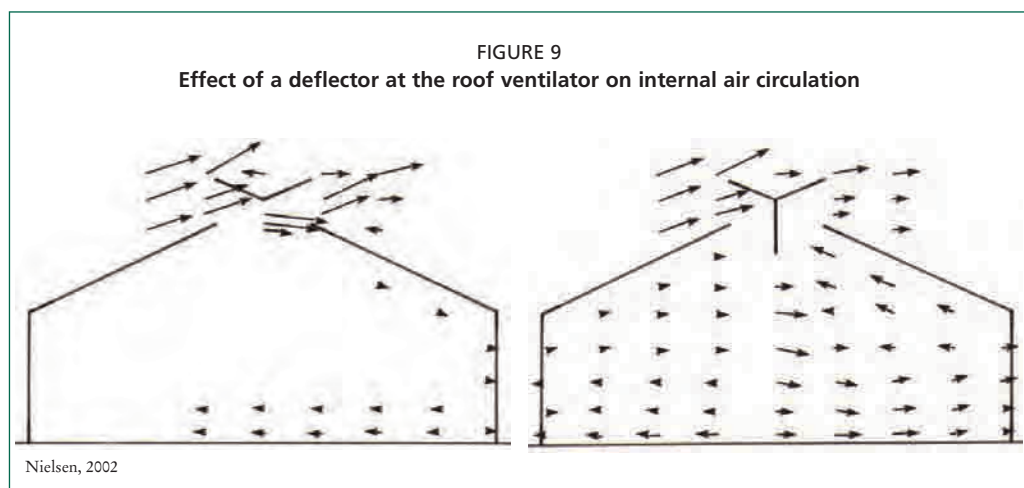
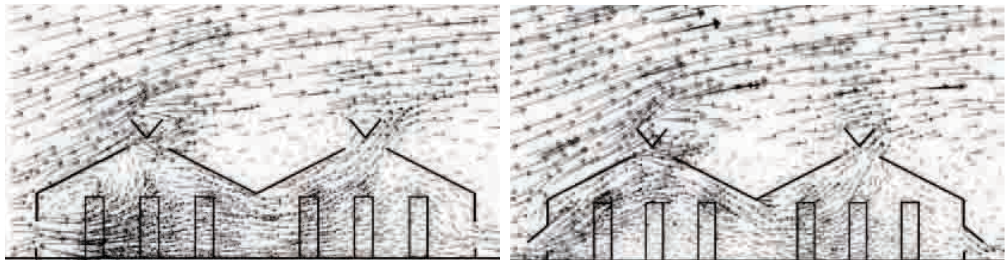


FIGURE 10
The effect of side vent configuration on the canopy zone ventilation and air exchange process
Roll up side vents (left); butterfly type side vents (right)



simulations using the CFD approach. The study evaluated both roll-up and butterfly-type side vent openings and various roof vent opening configurations (Figure 10). The maximum greenhouse ventilation rates were achieved when roll-up side vents were used in the sidewalls, and both side and roof vents were fully open. Use of the roll-up side vent considerably improved the ventilation rate in the plant canopy zone. This showed that ventilation in the plant canopy zone was significantly affected by the internal airflow patterns caused by different vent configurations (Figure 11).

Kacira *et al.* (2004b) demonstrated the importance of analysing the ventilation rates in the plant canopy zone as well as above the canopy. For example, under the same external wind speed and plant existence conditions, the ventilation rates in

FIGURE 11
Effects of external wind speed and vent configuration on ventilation rates
of greenhouse and plant canopy

Ventilation rate for greenhouse (m ³ m ⁻² min ⁻¹)								
Wind speed (m s ⁻¹)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
0.5	1.54	0.59	1.91	0.84	1.47	1.49	1.63	1.46
1.0	3.16	1.21	3.95	1.77	3.16	3.15	3.49	3.00
1.5	4.78	1.84	6.03	2.72	4.86	4.83	5.38	4.56
2.0	6.40	2.46	8.11	3.68	6.59	6.53	7.29	6.12
2.5	8.02	3.09	10.20	4.64	8.32	8.23	9.20	7.68
Ventilation rate for plant canopy zone (m ³ m ⁻² min ⁻¹)								
0.5	0.69	0.43	1.84	0.99	1.41	1.43	1.56	2.11
1.0	1.50	0.98	4.25	2.50	3.43	3.43	3.74	4.74
1.5	2.29	1.55	6.64	4.09	5.45	5.44	5.93	7.35
2.0	3.07	2.17	9.02	5.68	7.47	7.45	8.11	9.95
2.5	3.86	2.80	11.38	7.27	9.49	9.44	10.29	12.55

the greenhouse were found to be similar between the butterfly and roll-up curtain side vent configurations (Cases 1 and 3, Figure 11). However, the majority of the incoming air in the butterfly side vent cases did not reach the plant canopy zone. Conversely, the contribution of air entering the greenhouse from the windward roll-up curtain side vent for airflow uniformity and the achievement of higher ventilation rates in the plant canopy zone were found to be significant. The overall data showed that the ventilation in the plant canopy zone was considerably affected by the internal airflow patterns caused by different vent configurations.

Changes in the greenhouse slope

Increasing the greenhouse roof slope has a positive effect on the ventilation rate. Baeza (2007) compared the air exchange rate and internal airflow of greenhouses with slopes ranging from 12° to 32°. According to this study, ventilation sharply increased with roof slopes of up to 25°, after which the increase in ventilation was rather small. The low slope does not only affect the ventilation rate but also the air movement inside the greenhouse. Most of the airflow entering through the windward vent on a gentle slope attaches to the greenhouse cover, while with steeper slopes part of the airflow contributes to the ventilation of the first span and part of it moves on to the following span decreasing the attachment effect observed for lower slopes.

Size and type of ventilators

Baeza (2007) analysed the effect of ventilator size on greenhouse climate. He increased the flap ventilator size from 0.8 to 1.6 m in the first two and last two spans while maintaining the regular size of 0.8 m in the central spans. For a ten-span greenhouse, the increase in ventilator size had a significant effect on the ventilation rate. Besides, air movement in the crop area was enhanced. As a consequence, the temperature field was more uniform, the temperature difference in relation to the exterior was reduced and the stagnant air areas (warm spots) were significantly fewer in number and smaller in size. This study suggested that the greenhouse climate can be improved by making modest investments only in ventilators located in the first and last spans, which are critical to the air exchange process.

With regard to the ventilator type, Pérez-Parra (2004) compared flap ventilators and roll-up ventilators on the greenhouse roof under leeward and windward conditions. Flap ventilators were in all cases more effective at increasing ventilation rate than roll-up ventilators. Interestingly, the roll-up ventilator's performance was not affected by wind direction, while flap ventilators oriented windward side nearly doubled the air exchange of leeward flap ventilators.

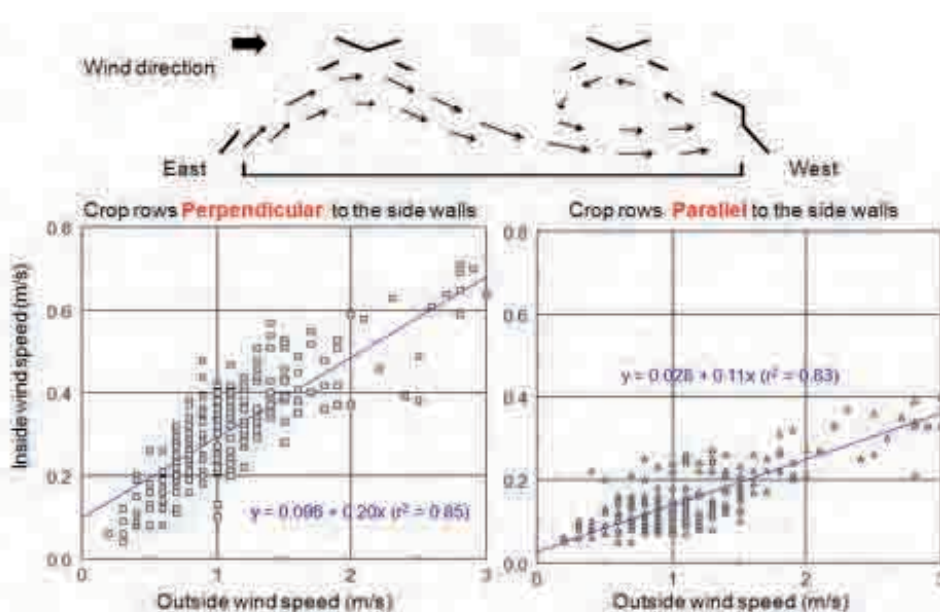
Crop row orientation

Sase (1989) conducted a ventilation study to compare the effect of the crop rows perpendicular and parallel to the sidewalls. As seen in Figure 12, the inside air velocity in the greenhouse with perpendicular rows was nearly twice that of the greenhouse with parallel rows; the crop canopy is a porous medium that offers resistance to the airflow, so it is recommended that the aisle between rows be oriented in the direction of the internal airflow. Sase's study was conducted in a small greenhouse where side ventilation prevailed over roof ventilation. For roof ventilation only, the effect of the crop orientation may be less important, since in roof ventilated greenhouses there is strong air movement over the crop area at a higher speed than the air in the canopy zone (Flores, 2010).

New greenhouse designs with improved ventilation

All the recently developed knowledge can be put together to produce better ventilation designs. Upcoming greenhouse models relying on natural ventilation should be narrow enough (maximum width 50 m) to avoid excessive temperature gradients; furthermore, they should have larger ventilators, especially in the first span facing prevailing winds. They will incorporate screens or deflectors to redirect the airflow towards the crop area producing a homogeneous mixture

FIGURE 12
Inside air velocity as a function of outside air velocity for a greenhouse
with crop rows parallel and perpendicular to the side wall



of the incoming and internal air, to have uniform growing conditions (Figure 13). Effective windward ventilation requires keeping an area between greenhouses free from obstacles. For proper ventilation, future greenhouse designs will not consider a single greenhouse, but a group or a greenhouse cluster, since the airflow in a greenhouse is affected by its surroundings.

Natural ventilation is the main method for greenhouse cooling, mainly because of the low energy consumption and reduced maintenance costs. However, natural ventilation relies on external conditions such as wind speed and direction and outside air temperature and humidity. Natural ventilation itself may not be sufficient to provide the desired environment under certain conditions. Thus, some other cooling techniques such as shading, mechanical ventilation or evaporative cooling, are used combined with natural ventilation. For a full discussion, it is necessary to consult the specific literature (Arbel *et al.*, 2006; Li *et al.*, 2006; Lorenzo *et al.*, 2004; Abdel-Ghany and Kozai, 2006; Abdel-Ghany *et al.*, 2006).

FIGURE 13
CFD study of the airflow pattern in a greenhouse with improved ventilation

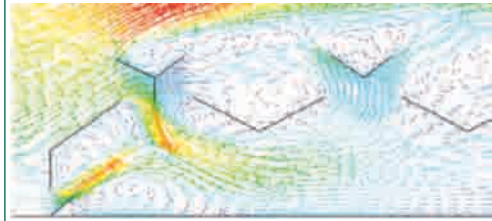


Plate 10

"Inversos" greenhouse. Prototype under evaluation. Fundacion Cajamar, Almería, Spain

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4. Greenhouse climate control and energy use

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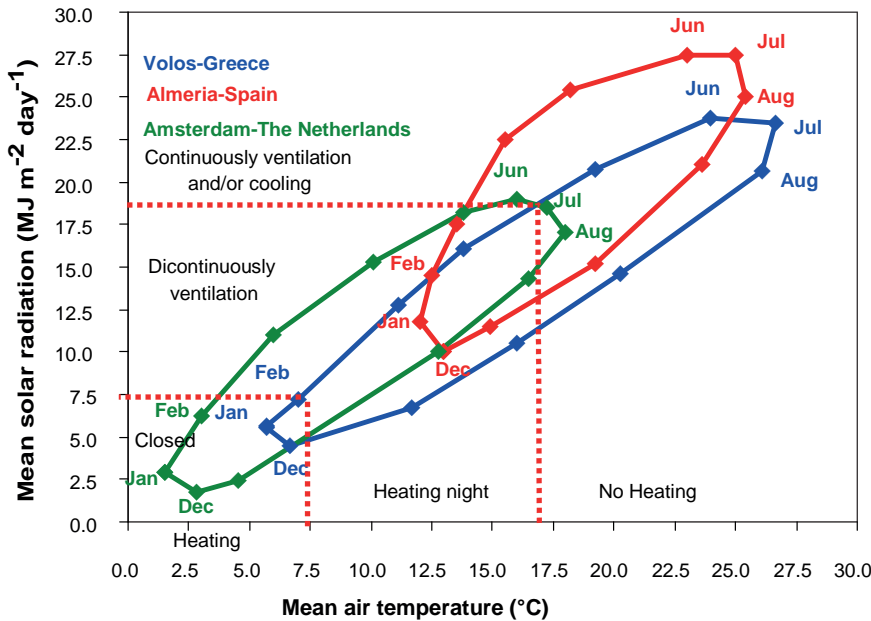
DRIVING FORCES FOR GREENHOUSE CLIMATE CONTROL AND SUSTAINABLE ENERGY USE IN MEDITERRANEAN GREENHOUSES

All greenhouse cultivation systems, regardless of geographic location, comprise fundamental climate control components; depending on their design and complexity, they provide more or less climate control, and condition to a varying degree plant growth and productivity.

Air temperature – as well as solar radiation and air relative humidity – is one of the most important variables of the greenhouse climate that can be controlled. It conditions not only crop development and production but also energy requirements, which can account for up to 40 percent of the total production costs. The majority of plants grown in greenhouses are warm-season species, adapted to average temperatures in the range 17–27 °C, with approximate lower and upper limits of 10 and 35 °C. If the average minimum outside temperature is < 10 °C, the greenhouse is likely to require heating, particularly at night. When the average maximum outside temperature is < 27 °C, ventilation will prevent excessive internal temperatures during the day; however, if the average maximum temperature is > 27–28 °C, artificial cooling may be necessary. The maximum greenhouse temperature should not exceed 30–35 °C for prolonged periods. The climograph of some Mediterranean and north European regions is shown in Figure 1. In temperate climates, as in the Netherlands, heating and ventilation enable the temperature to be controlled throughout the year, while at lower latitudes, such as in Almería (Spain) and Volos (Greece), the daytime temperatures are too high for ventilation to provide sufficient cooling during the summer. Positive cooling is then required to achieve suitable temperatures.

The second important variable is humidity, traditionally expressed in terms of relative humidity. Relative humidity within the range of 60–90 percent has little

FIGURE 1
Mean solar radiation versus mean air temperature for several locations around Europe



effect on plants. Values below 60 percent may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if relative humidity exceeds 95 percent for long periods, particularly at night as this favours the rapid development of fungus diseases such as *Botrytis cinerea*. The increased interest in maintaining adequate transpiration to avoid problems associated with calcium deficiency (Plate 1)



Plate 1
Pepper fruit with BER symptoms associated with calcium deficiency

has resulted in humidity being expressed in terms of the vapour pressure deficit (VPD) or the moisture deficit, both of which are directly related to transpiration. Maintaining the VPD above a minimum value helps to ensure adequate transpiration and also reduces disease problems. During the day, humidity can usually be reduced using ventilation. However, at night, unless the greenhouse is heated, the internal and external temperatures may be similar; if the external humidity is high, reducing the greenhouse humidity is not easy.

Following the energy crisis of the early 1980s, when limited energy supplies led to the first significant rise in energy prices, greenhouse energy use became a major research issue. With the recent increased interest in global warming and climate change, the use of fossil fuels is again on the political agenda and many governments have set maximum CO₂ emission levels for various industries, including the greenhouse sector. There are two main ways to increase greenhouse energy efficiency:

- reduce the energy input into the greenhouse system; and
- increase production per unit of energy.

The challenge is to meet both needs: improved energy efficiency combined with an absolute reduction in the overall energy consumption and related CO₂ emissions of the greenhouse industry. Technological innovations must focus on energy consumption for the return to productivity, quality and societal satisfaction.

There are a range of greenhouse system technologies which can be adopted by growers to improve climate control and energy use. However, there are numerous obstacles and constraints to overcome. The existing technology and know-how developed in north European countries are generally not directly transferable to the Mediterranean: high-level technology is beyond the means of most Mediterranean growers due to the high cost compared with the modest investment capacity; and know-how from north European growers is often inappropriate for the problems encountered in the Mediterranean shelters (Plate 2).

Where these technologies may be adopted, it is necessary to train and educate Mediterranean growers. To this end, specific research and development tasks have been initiated by the research institutes and extension services of Mediterranean countries. The issues addressed in this paper concern the means and best practices by which Mediterranean growers can alleviate the climate-generated stress conditions that inhibit the growth and the development of crops during the long warm season in a sustainable and energy-friendly way.



Plate 2

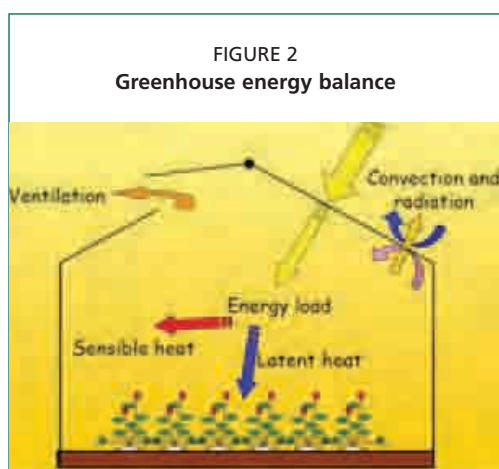
Internal view of parral (left, mainly found in Spain) and Venlo (right, mainly found in the Netherlands) type greenhouse

CLIMATE CONTROL

Ventilation cooling and shading

Removal of heat load is the major concern for greenhouse climate management in arid and semi-arid climate conditions. This can be achieved by:

- reducing incoming solar radiation;
- removing extra heat through air exchange; and
- increasing the fraction of energy partitioned into latent heat.



Shade screens and whitewash are the principle measures taken to reduce incoming solar radiation; greenhouse ventilation is an effective way to remove extra heat through air exchange between the inside and outside (when the outside air temperature is lower); and evaporative cooling is the common technique for reducing sensible heat load by increasing the latent heat fraction of dissipated energy. Other technological cooling solutions are available (heat pump, heat exchangers), but are not widely used, especially in the Mediterranean area because they require a high level of investment.

Ventilation

High summer temperatures mean that heat must constantly be removed from the greenhouse. A simple and effective way of reducing the difference between inside and outside air temperatures is to improve ventilation. Natural or passive ventilation requires very little external energy. It is based on the pressure difference between the greenhouse and the outside environment, resulting from the outside wind or the greenhouse temperature. If the greenhouse is equipped with ventilation openings (Plate 3), both near the ground and at the roof, hot internal air is replaced by cooler external air during hot sunny days when there is a slight wind. The external cool air enters the greenhouse through the lower side openings while the hot internal air exits through the roof openings due to the density difference between air masses of different temperature; the result is a lowering of the greenhouse temperature.

Sufficient ventilation is very important for optimal plant growth, especially in the case of high outside temperatures and solar radiation – common conditions during the summer in Mediterranean countries. In order to study the variables determining greenhouse air temperature and calculate the necessary measurements for temperature control, a simplified version of the greenhouse energy balance is formulated. Kittas *et al.* (2005) simplify the greenhouse energy balance to:

**Plate 3***Different types of ventilation opening*

$$Va = \frac{0.0003 \tau Rs, o - max}{\Delta T} \quad \text{Eq. 1}$$

where:

V_a is the ratio Q/A_g , Q is the ventilation flow rate ($\text{m}^3 [\text{air}] \text{s}^{-1}$)

A_g is the greenhouse ground surface area (m^2)

τ is the greenhouse transmission coefficient to solar radiation

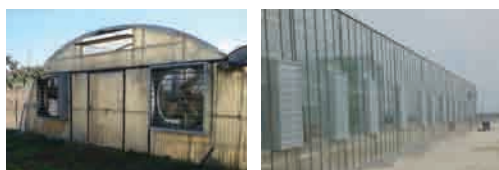
$Rs, o-max$ is the maximum outside solar radiation (W m^{-2})

ΔT is the temperature difference between greenhouse and outside air ($^{\circ}\text{C}$)

Using Equation 1, it is easy to calculate the ventilation requirements for several values of $Rs, o-max$ and ΔT . For the area of Magnesia, Greece, where values of outside solar radiation exceed 900 W m^{-2} during the critical summer period (Kittas *et al.*, 2005), a ventilation rate of about $0.06 \text{ m}^3 \text{s}^{-1} \text{m}^{-2}$ (which corresponds, for a greenhouse with a mean height of 3 m, to an air exchange of 60 h^{-1}) is needed in order to maintain a ΔT of about $4 ^{\circ}\text{C}$.

The necessary ventilation rate can be obtained by natural or forced ventilation; ventilators should, if possible, be located at the ridge, on the sidewalls and the gable. A total ventilator area equivalent to 15–30 percent of the floor area was recommended by White and Aldrich (1975); over 30 percent, the effect of additional ventilation area on the temperature difference was very small.

Some systems, including exhaust fan and blower, can supply high air exchange rates when needed. These simple and robust systems significantly increase the rate of air transfer from the greenhouse; consequently, the inside temperature can be kept at a level slightly above the outside temperature (Plate 4).

**Plate 4**

Fans for greenhouse forced ventilation

**Plate 5**

Insect-proof screen in roof opening

The principle of forced ventilation is to create airflow through the house. Fans suck air out on one side, and openings on the other side let air in. Forced ventilation by fans is the most effective way to ventilate a greenhouse, but it consumes electricity. It is estimated that the electrical energy requirements for ventilation of a greenhouse located in the Mediterranean are about 70 000 kWh per greenhouse ha.

Kittas *et al.* (2001) studied the influence of the greenhouse ventilation regime (natural or forced ventilation) on the energy partitioning of a well-watered rose canopy during several summer days in warm Mediterranean conditions (eastern Greece). When not limited by too low external wind speed, natural ventilation could be more appropriate than forced ventilation, creating a more humid and cooler environment

(albeit less homogeneous) around the canopy. Many researchers also studied the effects on greenhouse microclimate of insect-proof screens in roof openings (Plate 5). Fine mesh screens obstruct the airflow, resulting in reduced air velocity and higher temperature and humidity, as well as an increase in the thermal gradients within the greenhouse (Katsoulas *et al.*, 2006).

Shading

Natural or forced ventilation is generally not sufficient for extracting the excess energy during sunny summer days (Baille, 1999), and other cooling methods must be used in combination with ventilation. The entry of direct solar radiation

**Plate 6**

Thermal screen used for energy saving and greenhouse shading

through the covers into the greenhouse enclosure is the primary source of heat gain. The entry of unwanted radiation (or light) can be controlled by shading or reflection. Shading can be achieved in several ways: paints, external shade cloths, nets (of various colours), partially reflective shade screens (Plate 6), water film over the roof and liquid foams between the greenhouse walls. Shading is the last resort for cooling greenhouses, because it affects productivity; however, shading can in some cases result in improved quality. A method widely

Ventilation – GAP recommendations

- For a coastal area like Magnesia, Greece, where during the critical summer period, outside solar radiation exceeds 900 W m^{-2} , a ventilation rate of about $0.06 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-2}$ (corresponding, for a greenhouse with a mean height of 3 m, to an air exchange of 60 h^{-1}) is needed to maintain a ΔT of about 4°C . Natural ventilation allows for an air exchange rate of about 40 h^{-1} , above which, forced ventilation is necessary.
- For maximum efficiency, ventilators should, if possible, be located at the ridge, on the sidewalls and the gable.
- Total ventilator area equivalent to 15–30 percent of floor area is recommended; above 30 percent, the effect on the temperature difference is very small.
- If the external wind speed is not too low, natural ventilation can be more appropriate, creating a more humid and cooler (albeit less homogeneous) environment around the canopy.
- With roof ventilators, the highest ventilation rates per unit ventilator area are obtained when flap ventilators face the wind (100%), followed by flap ventilators facing away from the wind (67%); the lowest rates are obtained with rolling ventilators (28%).
- Systems such as exhaust fan and blower can supply high air exchange rates whenever needed. These simple and robust systems significantly increase the air transfer rate from the greenhouse, maintaining the inside temperature at a level slightly higher than the outside temperature by increasing the number of air changes.
- Forced ventilation by fans is the most effective way to ventilate a greenhouse, but electricity consumption is high. The estimated electrical energy requirements for ventilation of a greenhouse located in the Mediterranean are about 70 000 kWh per greenhouse ha.
- Ventilation fans should develop a capacity of about 30 Pa static pressure (3 mm on a water gauge), they should be located on the lee side or the lee end of the greenhouse, and the distance between two fans should not exceed 8–10 m. Furthermore, an inlet opening on the opposite side of a fan should be at least 1.25 times the fan area. The velocity of the incoming air must not be too high in the plant area; air speed should not exceed 0.5 m s^{-1} . The openings must close automatically when the fans are not in operation.
- With fan cooling alone (no evaporative cooling), little advantage can be derived from increasing airflow rates beyond 0.05 m s^{-1} .

adopted by growers because of its low cost is white painting, or whitening, of the cover material. The use of screens has been progressively accepted by growers and the last decade has seen an increase in the area of field crops cultivated under screenhouses (Cohen *et al.*, 2005). Roof whitening, given its low cost, is common practice in the Mediterranean Basin.

Baille *et al.* (2001) reported that whitening on glass material enhanced slightly the PAR (photosynthetically active radiation) proportion of the incoming solar irradiance, thus reducing the solar infrared fraction entering the greenhouse – a potential advantage compared with other shading devices, especially in warm

countries with high radiation load during summer. Another advantage of whitening is that it does not affect ventilation, while internal shading nets negatively affect the performance of roof ventilation. Whitening also significantly increases the fraction of diffuse irradiance, which is known to enhance radiation-use efficiency.

Screens mounted inside the greenhouse also contribute to decreasing the inside wind speed, thus lessening the leaf boundary layer and restraining the availability of CO₂ near the leaf surface. It is not clear whether shading nets are best used throughout the growth cycle or only during the most sensitive stages when the crops have a low leaf area and the canopy transpiration rate cannot significantly contribute to the greenhouse cooling (Seginer, 1994).

Evaporative cooling

One of the most efficient solutions for alleviating climatic conditions is to use evaporative cooling systems, based on the conversion of sensible heat into latent heat through evaporation of water supplied directly into the greenhouse atmosphere (mist or fog system, sprinklers) or via evaporative pads (wet pads). Evaporative cooling allows simultaneous lowering of temperature and vapour pressure deficit, and its efficiency is higher in dry environments. The advantage of mist and fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, eliminating the need for forced ventilation and airtight enclosure. Before installing a system, the air- and waterflow rates required must be calculated.

Fog system

Water is sprayed as small droplets (in the fog range, 2–60 nm in diameter) with high pressure into the air above the plants in order to increase the water surface in contact with the air (Plate 7). Freefall velocity of these droplets is slow and the air streams inside the greenhouse easily carry the drops. This can result in high efficiency of water evaporation combined with keeping the foliage dry. Fogging is also used to create high relative humidity, along with cooling inside the greenhouse. A wide range for fog system cooling efficiency ($n_{f,cool}$) is reported



Plate 7

Fog system used for greenhouse cooling

in the literature. According to Arbel *et al.* (2003), increased efficiency in the cooling process in relation to water consumption can be expected if fogging is combined with a reduced ventilation rate. Furthermore, a close relationship has been observed between $n_{f,cool}$ and system operation cycling (Abdel-Ghany and Kozai, 2006). Similar values for $n_{f,cool}$ have been reported by Li *et al.* (2006), who concluded that fog cooling efficiency increases with spray rate and decreases with ventilation rate.

Evaporative cooling – GAP recommendations 1: fog system

- Evaporative cooling allows simultaneous lowering of temperature and vapour pressure deficit and can lead to greenhouse air temperatures lower than the outside air temperature. Efficiency increases in dry environments.
- The advantage of mist and fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, eliminating the need for forced ventilation and airtight enclosure. Before installing a system, the air- and waterflow rates required must be calculated.
- Fog systems can be high (40 bars) or low (5 bars) pressure systems; high pressure systems are more effective than low pressure.
- The nozzles of the fog system should be located at the highest possible position inside the greenhouse to allow water evaporation before the water drops to the crop or the ground.
- During operation of the fog system, a vent opening of 20 percent of the maximum aperture should be maintained.
- Nozzles with fans provided 1.5 times better evaporation ratio and three times wider cooling area than nozzles without fans. Nozzles with fans produce a lower and more uniform air temperature.

Fan and pad cooling

The fan-and-pad cooling system (Plate 8) is most commonly used in horticulture. Air from outside is blown through pads with as large a surface as possible and which are kept permanently wet by sprinkling. The water from the pads evaporates and cools the air; outside air humidity must therefore be low. There are basically two systems of fan-and-pad cooling: the negative-pressure system and the positive-pressure system.

- The negative-pressure system consists of a pad on one side of the greenhouse and a fan on the other. The fans suck the air through the pad and through the greenhouse. The pressure inside the greenhouse is lower than the pressure outside; hot air and dust can therefore get into the greenhouse. There is a temperature gradient from pad to fan.

**Plate 8**

Pad (left) and fan (right) greenhouse cooling system

- The positive-pressure system consists of fans and pads on one side of the greenhouse and vents on the other. The fans blow the air through the pads into the greenhouse. The pressure inside the greenhouse is higher than outside; dust cannot get into the greenhouse.

In order to achieve optimal cooling, the greenhouse should be shaded. The waterflow rate, water distribution system, pump capacity, recirculation rate and output rate of the fan-and-pad cooling system must be carefully calculated and designed to provide a sufficient wetting of the pad and to avoid deposition of material.

The manufacturers' guidelines for pad selection and installation must be observed; furthermore, there are numerous considerations when designing a fan-and-pad cooling system. First, cooling efficiency should provide inside air humidity of about 85 percent at the outlet; higher air humidity slows down the transpiration rate of the plants. Plant temperature can then increase above air temperature. It is important that the pad material have a high surface, good wetting properties and high cooling efficiency. It should cause little pressure loss, and should be durable. The average thickness of the pad is 100–200 mm. It is essential that the pad be free of leaks through which air could pass without making contact with the pad. Different pad materials are available, such as wood, wool, swelling clay minerals, and specially impregnated cellulose paper.

The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0.75–1.5 m s⁻¹. Excessive velocities may cause problems with drops entering the greenhouse. The pad area should be about 1 m² per 20–30 m² greenhouse area. The maximum fan-to-pad distance should be 30–40 m.

Pads may be positioned horizontally or vertically (more often the latter). Vertical pads are supplied with water from a perforated pipe along the top edge. In the case of horizontal pads, the water is sprayed over the upper surface. The water distribution must ensure even wetting of the pad. Pads have to be protected from direct sunlight to prevent localized drying out: salt and sand might clog them if they become dry. In areas with frequent sandstorms it is recommended to protect the wet pad with a thin dry pad serving as a sand filter. The pads have to be located and mounted in a way which permits easy maintenance and cleaning. They should be located on the side facing the prevailing wind.

Belt-driven or direct-driven propeller fans are used. Direct-driven fans are easier to maintain. Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10 percent in the ventilation rate will be needed. The distance between fans should not exceed 7.5–10 m, and fans should not discharge towards the pads of an adjacent greenhouse less than 15 m away. All

exhaust fans should be equipped with automatic shutters to prevent air exchange when fans are not operating, and also to prevent back-draught when some are not being used.

When starting the cooling system, the waterflow through the pad should be turned on first to prevent the pads from clogging. Fans should not be started before the whole pad has been completely wetted. When stopping the cooling system in the evening, the fan should be turned off before the waterflow through the pad. It is recommended to operate the cooling system by a simple control system depending on the inside temperature. The airflow rate depends on the solar radiation inside the greenhouse – that is, on the cladding material and shading – and on the evapotranspiration rate from the plants and soil. The airflow rate can be calculated by an energy balance. Generally, a basic airflow rate of 120–150 m³ per m² greenhouse area per hour will permit satisfactory operation of an evaporative cooling system.

Evaporative cooling – GAP recommendations 2: fan and pad

- The pad material should have a high surface, good wetting properties and high cooling efficiency. Suggested pad thickness is 200 mm. It is very important that there are no leaks where air can pass through without making contact with the pad.
- The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0.75–1.5 m s⁻¹. The pad area should be about 1 m² per 20–30 m² greenhouse area. The maximum fan-to-pad distance should be 40 m.
- Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10 percent in the ventilation rate is necessary. The distance between fans should not exceed 7.5–10 m, and fans should not discharge towards the pads of an adjacent greenhouse less than 15 m away.
- When starting the cooling system, the waterflow through the pad should be turned on first to prevent the pads from clogging. When stopping the cooling system in the evening, the fan should be turned off before the waterflow through the pad.
- A basic airflow rate of 120–150 m³ per m² greenhouse area per hour will permit satisfactory operation of an evaporative cooling system.

Heating

Greenhouse heating is essential even in countries with a temperate climate, like the Mediterranean region, in order to maximize crop production in terms of quantity and quality and thus to increase overall efficiency. Heating costs are not only directly connected to profitability, but in the long term they may determine the survival of the greenhouse industry. In addition to the costs of high energy consumption, heating is associated with environmental problems through the emission of noxious gases.

Heating needs

There are various ways to calculate greenhouse heating needs (H_g) (W). The simplest is proposed by ASAE (2000):

$$H_g = U A (T_i - T_o) \quad \text{Eq. 2}$$

where:

U = heat loss coefficient ($\text{W m}^{-2} \text{K}^{-1}$) (see Table 1)

A = exposed greenhouse surface area (m^2)

T_i = inside air temperature (K)

T_o = outside air temperature (K)

Note that the estimation of greenhouse needs using Equation 2 did not take into account heat loss due to leakage. However it is a simple formula which can be used in order to estimate heating needs according to the greenhouse covering area and the desired temperature difference between inside and outside air.

TABLE 1
Total heat loss coefficient U at wind speed of n m/s

Covering materials	U value $\text{W/m}^2/\text{K}$
Single glass	6.0–8.8
Double glass, 9 mm air space	4.2–5.2
Double acrylic 16 mm	4.2–5.0
Single plastic	6.0–8.0
Double plastic	4.2–6.0
Single glass plus energy screen of	
- single film, non-woven	4.1–4.8
- aluminized single film	3.4–3.9

ASAE, 2000

Calculation of greenhouse heating needs

1. Measure the first three dimensions of the greenhouse:
 - Measure the length, width and height of the structure (to where the roof begins).
2. Measure the ridge of the greenhouse:
 - Measure the distance between the ground and the tip of the greenhouse's roof.
3. Measure the slope of the greenhouse roof:
 - The slope is the distance from the tip of the roof to the bottom of the roof.
4. Determine the surface area of the greenhouse's roof slope and two walls:
 - Use the formula: $2 \times (H + S) \times L$
where H = height, S = roof slope and L = length.
5. Determine the surface area of the remaining two walls:
 - Use the formula: $(R + H) \times W$
where R = ridge, H = height and W = width.
6. Determine the total surface area of the greenhouse:
 - Add together the results from step 4 and step 5.
7. Calculate the desired temperature difference:
 - Determine the best temperature for the interior of the greenhouse.
 - Determine the average coldest temperature for the area surrounding the greenhouse.
 - Determine the difference between the two temperatures.
8. Estimate the overall heat loss coefficient:
 - According to the covering material, refer to Table 1.
9. Estimate the heating needs of the greenhouse:
 - Multiply the total surface area of the greenhouse (step 6) by the temperature difference (step 7) by the overall heat loss coefficient (step 8).

Heating systems

The heating system must provide heat to the greenhouse at the same rate at which it is lost. There are several popular types of heating systems for greenhouses. The most common and least expensive is the unit heater system.

Unit heaters

Warm air is blown from unit heaters with self-contained fireboxes. Heaters are located throughout the greenhouse, each heating a floor area of 180–500 m². The typical cost, including installation is €4–8/m² of greenhouse floor.

Central heating

Steam or hot water is produced, plus a radiating mechanism in the greenhouse to dissipate the heat (Plate 9). The typical cost of a central boiler system for 1 ha, including heat distribution and installation, is €30–80/m² of greenhouse floor space, depending on the number of heat zones and the exact heat requirement.

**Plate 9**

Central boiler (left) and heating pipes for dissipating the produced heat (right)

Unlike unit heater systems, a portion of the heat from central boiler systems is delivered to the root and crown zone of the crop, resulting in improved growth and to a higher level of disease control. Placement of heating pipes is very important as it is directly related to heat loss; for example, the placement of pipes in the walls resulted in high losses through the sides.

**Plate 10**

Wall pipes

Wall pipe coils. Perimeter-wall heating can provide part of the additional heat requirement and contribute to a uniform thermal environment in the greenhouse. Both bare and finned pipe applications are common. Side pipes should have a few centimetres of clearance on all sides to permit the establishment of air currents and should be located low enough to prevent the blockage of light entering through the sidewall.

Overhead pipe coils. An overhead coil of pipes across the entire greenhouse results in heat loss through the roof and gables. The overhead coil is not the most desirable source of heat, as it is located above the plants; nevertheless, overhead heating systems can provide the additional heat required for winter months. They can also be used to reduce the risk of *Botrytis cinerea* outbreak, a major concern for many greenhouse growers

In-bed pipe coils. When the greenhouse layout allows it, the in-bed coil is preferable. By placing the heating pipes near the base of the plants, the roots and crown of the plants receive more heat than in the overhead system. Air movement caused by the warmer underbench pipe reduces the humidity around the plant. Heat is also kept lower in the greenhouse resulting in better energy efficiency. Such systems are suitable for plants grown on benches, fixed tables, and rolling or transportable tables.

Floor pipe coil. Floor heating is more effective than in-bed pipe coil heating. In addition to the advantages of in-bed coils, floor heating has the ability to dry the floor quickly. This is essential when flood floors are used for irrigation/fertilization. In this system, plants are set on the floor, which makes drying the floor difficult. Air movement caused by the warmer floor reduces the humidity around the plant. Such systems are suitable for plants directly grown on the floor, flooded-floor areas or work areas.



Plate 11
Pipe/rail heating systems

Pipe/rail heating systems

These systems maintain uniform temperatures with a positive effect on the microclimate. Air movement caused by the warmer pipe/rail reduces humidity around the plant. Such systems are suitable for vegetable production (Plate 11).

Radiant heater systems

These heaters emit infrared radiation, which travels in a straight path at the speed of light. The air through which the radiation travels is not heated. After objects such as plants, walks and benches have been heated, they will warm the air surrounding them. Air temperatures in infrared-radiant-heated greenhouses can be 3–6 °C cooler than in conventionally heated greenhouses with equivalent plant growth. Grower reports on fuel savings suggest a 30–50 percent fuel reduction with the use of low energy infrared-radiant heaters, as compared with the unit heater system.

Thermostats and controls

Various thermostat and environmental controllers are available for commercial greenhouse production. Sensing devices should be placed at plant level in the greenhouse: thermostats at eye level are easy to read but do not provide the necessary input for optimum environmental control. An appropriate number of sensors are needed throughout the production area. Environmental conditions can vary significantly within a small distance. Thermostats should not be placed in the direct rays of the sun as this would result in poor readings; they should be mounted facing north or in a protected location. It may be necessary to use a small fan to pull air over the thermostat to get appropriate values.

Energy heaters and generators

The risks associated with electrical power are always present. Heaters and boilers depend on electricity, and if a power failure occurs during a cold period, such as a heavy snow or ice storm, crop loss due to freezing is likely. A standby electrical

generator is essential for any greenhouse operation. Although it may never actually be used, even if it is needed for just one critical cold night, it becomes a highly profitable investment. A minimum of 1 kW of generator capacity is required per 200 m² of greenhouse floor area.

Heating for antifrost protection

Heating can be used to protect crops from freezing. It can also keep the greenhouse air temperature at levels above critical thresholds for condensation control. When not equipped with heavy and complicated heating systems, a unit heater is usually enough. Listed below are other useful recommendations for heating a greenhouse in order to avoid fruit freezing:

- Back the north wall to an existing structure such as a house or outbuilding for additional wind protection and insulation.
- Use water to store heat (a simple passive solar heating system): barrels or plastic tubes filled with water inside the greenhouse capture the sun's heat, which is then released at night when temperatures drop.
- Insulate the greenhouse; insulate plastic greenhouses with a foam sheet – easily placed over the structure at night and removed during the day; install an additional layer of plastic to the interior of the greenhouse for added insulation.

Heating checklist – Structure

- Covering
 - Replace damaged or excessively darkened panels
 - Repair or seal cracks or holes
 - Remove unnecessary shading compound to allow light penetration
- Vent system
 - Repair or adjust vents to reduce cracks at mating surfaces
- Thermal blankets
 - Operate through a complete cycle
 - Check that all seals close properly
 - Repair all holes and tears

Heating checklist (cont.) – Heating system

- Unit heater (forced air)
 - Check and clean burner nozzles
 - Ensure that adequate outside air is available to burners
 - Check flues for proper size and obstructions
 - Check fuel lines for leaks
 - Check heat exchangers for cracks and carbon and dirt buildup
- Boilers (steam or hot water)
 - Check and ensure that safety or relief valves are operative and not leaking
 - Clean tubes – both fireside and waterside
 - Clean blower fan blades
 - Maintain accurate water treatment records
 - Check boiler operating pressure and adjust to proper pressure
 - Insulate hot water heater or boiler
 - Make sure wiring is in good condition
 - Make sure good quality water is available for the system
- Steam or hot water delivery and return system
 - Fix pipe leaks
 - Be sure that there is enough pipe to transfer the available heat to maintain desired greenhouse temperatures
 - Clean heating pipes as needed, clean both inside and out, and clean heating fins
 - Adjust valve seats and replace if needed
 - Check for the proper layout of piping for maximum efficiency
- Control
 - Ensure that heating and cooling cycles or stages do not overlap
 - Check for accuracy of thermostats with a thermometer
 - Calibrate, adjust or replace thermostats
 - Make sure that thermostats are located near to or at plant level and not exposed to nearby heat sources
- Stand-by generator
 - Clean and check battery
 - Drain and refill generator fuel tanks
 - Check fuel tank and lines for leaks
 - Start and run weekly

Heating – GAP recommendations

- Keep a backup heating plan in case heater fails.
- Do not over seal the greenhouse in winter: bad ventilation leads to humidity problems.
- Have a weather station that serves as a greenhouse internal temperature monitor.
- Buy and use a thermostat to maintain the constant minimum temperature in your greenhouse.
- Use greenhouse fans to circulate the heat from greenhouse ceiling to floor.
- Install an alarm system for fire, smoke and CO₂ buildup.
- Replace greenhouses after 15–20 years (depending on the type of structure, materials used and climate control equipment).

CO₂ enrichment

The lack of climate control in many greenhouses in Mediterranean countries results in an inadequate microclimate that negatively affects yield components and input-use efficiency. CO₂ enrichment is essential to increase quality of produce; indeed, continuous or periodical increase of CO₂ inside the greenhouse may lead to an increase of over 20 percent in fruit production for both dry and fresh matter (Shanchez-Guerrero *et al.*, 2005). Better control of the greenhouse aerial environment can improve marketable yield and quality, and extend the growing season (Baille, 1999). Inside an unenriched greenhouse, the CO₂ concentration drops below the atmospheric level whenever the CO₂ consumption rate by photosynthesis is greater than the supply rate through the greenhouse vents. The poor efficiency of ventilation systems in low-cost greenhouses in Mediterranean countries, coupled with the use of insect-proof nets (Muñoz *et al.*, 1999), explains the relatively high CO₂ depletion (about 20% or more) reported in southern Spain (Lorenzo *et al.*, 1990). Possible solutions are:

- increase the ventilation rate through forced air;
- improve design and management of the ventilation system; or
- provide CO₂ enrichment.

The latter is widely adopted in the greenhouse industry in northern Europe to enhance crop photosynthesis under the low radiation conditions that prevail during winter. Enrichment reportedly increases crop yield and quality under a CO₂ concentration of 700–900 $\mu\text{mol mol}^{-1}$ (Nederhoff, 1994).

An important constraint is the short time period available for the efficient use of CO₂ enrichment, due to the need to ventilate for temperature control (Enoch, 1984). The fact that greenhouses have to be ventilated during a large part of the day makes it uneconomical to maintain a high CO₂ concentration during the day.

However, some authors advise supplying CO₂ even when ventilation is operating (Nederhoff, 1994) in order to maintain the same CO₂ concentration both in the greenhouse and outside, enriching to levels of about 700–800 $\mu\text{mol mol}^{-1}$ when the greenhouse is kept closed (usually in the early morning and the late afternoon).

In the absence of artificial supplies of carbon dioxide in the greenhouse environment, the CO₂ absorbed during photosynthesis must ultimately come from the external environment through the ventilation openings. The concentration of CO₂ within the greenhouse must be lower than that outside in order to obtain inward flow. Since potential assimilation is heavily dependent on carbon dioxide concentration, assimilation is reduced, whatever the light level or crop status. The ventilation of the greenhouse implies a trade-off between ensuring inflow of CO₂ and maintaining an adequate temperature within the greenhouse, particularly during sunny days.

Stanghellini *et al.* (2008) applied a simple model for estimating potential production loss, using data obtained in commercial greenhouses in Almería, Spain, and Sicily, Italy. They analysed the cost, potential benefits and consequences of bringing more CO₂ into the greenhouse: either through increased ventilation, at the cost of lowering temperature, or through artificial supply. They found that while the reduction in production caused by depletion is comparable to the reduction resulting from lower temperatures caused by ventilation to avoid depletion, compensating the effect of depletion is much cheaper than making up the loss by heating.

Optimal CO₂ enrichment depends on the margin between the increase in crop value and the cost of providing the CO₂. Attempting to establish the optimal concentration by experiment is not feasible because the economic value of enrichment is not constant but varies with solar radiation through photosynthesis rate, and with greenhouse ventilation rate through loss of CO₂ (Bailey and Chalabi, 1994). The optimal CO₂ setpoint depends on several influences: the effect of CO₂ on the photosynthetic assimilation rate, the partitioning to fruit and to vegetative structure, the distribution of photosynthate in subsequent harvests, and the price of fruit at those harvests, in addition to the amount of CO₂ used, greenhouse ventilation rate and the price of CO₂.

The principal source of CO₂ enrichment in the greenhouse used to be pure gas; nowadays more frequent use is made of the combustion gases from a hydrocarbon fuel, for example, low sulphur paraffin, propane, butane or natural gas and more recently also from biogas. In these cases, attention should be given to monitoring the SO₂, SO₃ and NO_x levels, which can damage the crops even at very low concentrations.

Dehumidification

Condensation refers to the formation of drops of water from water vapour. Condensation occurs when warm, moist air in a greenhouse comes into contact with a cold surface such as glass, fibreglass, plastic or structural members. The air in contact with the cold surface is cooled to the surface temperature. If the surface temperature is below the dew point temperature of the air, the vapour in the air will condense onto the surface. Condensation is heaviest in greenhouses from sunset to several hours after sunrise. During daylight hours, there is sufficient heating from solar radiation to minimize or prevent condensation, except on very cold, cloudy days. Greenhouses are most likely to experience heavy condensation at sunrise or shortly before. Condensation is a symptom of high humidity and can cause significant problems (e.g. germination of fungal pathogen spores, including *Botrytis* and powdery mildew.) Condensation can be a major problem – at certain times of the year, impossible to avoid entirely.

How to dehumidify the greenhouse

Combined use of heating and ventilation

A common dehumidification practice is simply to open the windows, allowing moist greenhouse air to be replaced by relatively dry outside air. This method does not consume any energy when excess heat is available in the greenhouse and ventilation is needed to reduce the greenhouse temperature. However, when the ventilation required to reduce the temperature is less than that needed to remove moisture from the air, dehumidification consumes energy. Warm greenhouse air is replaced by cold dry outside air, lowering the temperature in the greenhouse.

Absorption using hygroscopic material

There has been little research on the application of hygroscopic dehumidification in greenhouses, because installation is complex and the use of chemicals is not favourable. During the process, moist greenhouse air comes into contact with the hygroscopic material, releasing the latent heat of vaporization as water vapour is absorbed. The hygroscopic material has to be regenerated at a higher temperature level. A maximum of 90 percent of the energy supplied to the material for regeneration can be returned to the greenhouse air with a sophisticated system involving several heat exchange processes including condensation of the vapour produced in the regeneration process.

Condensation on cold surfaces

Wet humid air is forced to a cold surface located inside the greenhouse and different from the covering material. Condensation occurs on the cold surface, the water is collected and can be reused, and the absolute humidity of the wet greenhouse air is reduced. One metre of finned pipe used at a temperature of 5 °C can remove 54 g of vapour per hour from air at a temperature of 20 °C and with 80 percent relative humidity.

Forced ventilation usually with combined use of a heat exchanger

Mechanical ventilation is applied to exchange dry outside air with moist greenhouse air, exchanging heat between the two airflows. Based on the results of Campen *et al.* (2003), a ventilator capacity of $0.01 \text{ m}^3 \text{ s}^{-1}$ is sufficient for all crops. The energy needed to operate the ventilators is not considered; an experimental study (Speetjens, 2001) showed the energy consumption by the ventilators to be less than 1 percent of the energy saved.

Anti-drop covering materials

The use of anti-drop covering materials is an alternative technology for greenhouse dehumidification. “Anti-dripping” films contain special additives which eliminate droplets and form instead a continuous thin layer of water running down the sides. The search for anti-drip cover materials has been mainly focused on the optical properties of the cover materials.

When should dehumidification take place?

- Dusk: Reduce humidity to 70–80% as night falls to prevent condensation.
- Dawn: Reduce humidity to prevent condensation, and jumpstart transpiration as the sun rises.

Dehumidification – GAP recommendations

- Remove any excess sources of water in the greenhouse.
- Open the windows or the door to the greenhouse and allow excess moisture to escape ventilation.
- Turn on the greenhouse fan to improve air circulation.
- Purchase a humidity controller or a dehumidifier for use in the greenhouse.
- Use thermal screens at night to prevent radiative heat loss from plant surfaces.
- Place radiant heat sources near the crop to keep plant surfaces slightly warmer than air.

RATIONAL USE OF ENERGY AND RENEWABLE ENERGY SOURCES

Rational energy use is fundamental since energy accounts for a substantial proportion of total production costs. For northwest European conditions with heated greenhouses, annual energy consumption for conditioning is high (1 900 MJ m⁻² in Scandinavia). In Mediterranean areas, less energy is used (500–1 600 MJ m⁻²), but heating is increasingly adopted to achieve early production and a constant quantitative-qualitative yield, leading to higher energy use. Improved environmental control (e.g. more CO₂ supply, additional lighting), intensified production schemes and use of cooling systems all increase energy consumption. Average energy use accounts for 10–30 percent of total production costs, depending on the region.

Increase in production per unit of energy (energy efficiency) can be achieved through reduction of energy use and/or improvement of production. The major challenge in greenhouse operation is to find ways to contribute to improved energy efficiency combined with an absolute reduction of the overall energy consumption. The emission of CO₂ depends on the total use and type of fossil fuel. For example, when coal is used, CO₂ emission is 80–100 kg/MJ; for diesel, 75 kg/MJ; for propane, 65 kg/MJ; while for natural gas it is about 58 kg/MJ.

In general, the Mediterranean and north European regions have similar objectives with respect to optimizing production efficiency:

- autumn/winter – maximize the radiation quantity and minimize the energy loss;
- spring/summer – reduce high temperatures.

For rational use of energy (or fossil fuels) and reduction of greenhouse energy consumption, greater investment is required in order to achieve:

- efficient use of energy (i.e. amount of product per input of energy);
- reduction of energy requirement; and
- replacement of fossil fuels by more sustainable sources.

Energy-efficient climate control

Rational use of energy largely depends on energy-efficient greenhouse environmental control, which requires knowledge of the physiological processes (photosynthesis and transpiration, crop growth and development) in relation to the various environmental factors (temperature, light, humidity and carbon dioxide). However, to achieve the maximum benefits of energy-efficient environmental control, it is essential that the greenhouse itself and the control equipment (heating and ventilation system, CO₂ supply, lighting) are properly designed and frequently checked (at least at the start and once during the growth season). For example, optimized designs of pipe heating systems may prevent uneven temperature distribution and subsequent loss of energy and crop production.

Temperature control

Wind-dependent heating

One way to substantially reduce energy use is to lower heating temperatures: a 1 °C reduction gives an energy saving of around 10 percent. However, lowering temperature slows down growth and development of most crops and may significantly reduce quality. Thus a lower heating temperature will save energy, but is generally not economically feasible as it results in reduced crop production which is not usually compensated for by the lower energy costs. A more economic application of reduced heating temperatures is wind-dependent temperature control. Heat losses increase linearly as wind speed increases, therefore, energy can be saved by reducing the heating setpoints when it is windy and compensating for this using increased temperatures at low wind speeds. This method results in energy savings of 5–10 percent.

Temperature integration

Another option for energy-efficient temperature control is the so-called temperature integration (TI) method. This method is based on the fact that the effect of temperature on crop growth and production depends on the 24-hour average temperature rather than distinct day/night temperatures (de Koning, 1988). However, there are limits to this approach and plants have to be grown within the sub- and supra-optimal temperatures (e.g. tomato: > 15 °C and < 30 °C, and chrysanthemum: > 14 °C and < 24 °C) to prevent reduced quality and/or production levels due to poor fruit or flower development.

In southern regions in particular, the TI strategy can be implemented using higher than normal ventilation temperatures to maximize heating due to solar gain and to compensate these temperatures by running lower temperatures at night or on dull days.

In general, application of TI leads to higher temperatures during daytime and lower temperatures at night. However, the approach of using higher ventilation setpoints can also be combined with the use of lower day heating setpoints and higher temperatures under thermal screens at night. The aim is to fully exploit solar gain and, when additional heat is required, to add it preferably at night when heat losses are limited due to the closed thermal screen. There are potential energy savings of up to 20 percent; Rijdsdijk and Vogelesang (2000) demonstrated an 18 percent energy saving in pot plants, rose and sweet pepper with a band width of 8 °C. However, when setting band widths for temperature integration, a balance must be found between maximizing energy savings and minimizing detrimental effects on yield or quality. The balance varies enormously depending on the crop, so specific crop knowledge is required.

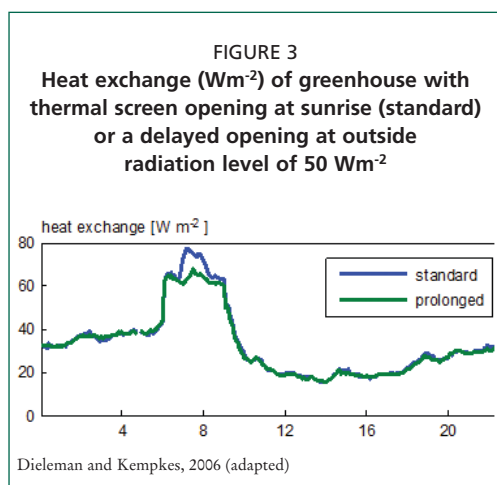
Humidity control

On a year round basis, a major fraction of the energy transfer from the greenhouse to the environment is by natural ventilation. Under relatively low radiation and moderate ambient temperatures, natural or forced ventilation is generally used to prevent high humidity. Consequently a substantial fraction (5–20%) of the total energy consumption is related to humidity control. Although high humidity is generally associated with increased risk of fungal diseases and reduced quality (e.g. *Botrytis*, blossom end rot), it may also be positive for crop production and quality (Montero, 2006). Reducing the level of humidity of the air is costly as a result of the energy required and should be assessed against the added value of the crop. An increase in the humidity setpoint of 5 percent decreases the energy consumption by approximately 6 percent. To reduce “humidity control related” energy consumption, there are several options:

- higher humidity setpoints
- reduction of the transpiration level of the crop
- active dehumidification with heat recovery

Thermal screens

Energy-efficient thermal screen control involves achieving a balance between the production and quality effects related to humidity and light, and energy saving. Energy-efficient (humidity) screen control can be achieved by opening the screen prior to the ventilators to maintain a given humidity setpoint. By closing the screen at night, an additional energy saving (4%) can be obtained without any production losses if the opening of the screen is delayed until radiation levels are outside 50–150 W m^{-2} ; the heat exchange of the greenhouse is thereby reduced for a longer period during the early morning hours (Figure 3).



Reduction of transpiration

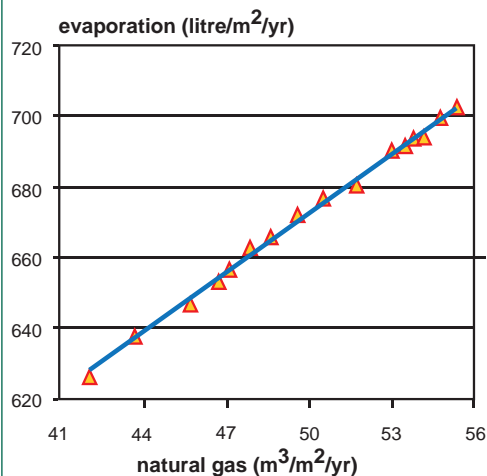
Reduction of transpiration may have positive effects on energy efficiency since lower transpiring crops bring less water into the air and therefore require less energy for humidity control under low irradiation conditions (Figure 4). Higher CO_2 levels, by decreasing stomatal conductance and thus transpiration, may also improve energy efficiency by 5–10 percent without affecting photosynthesis or growth. Controlled reduction of the leaf area for crops with a high leaf area index, such as pepper, may reduce energy use without any impact on production. Halving the leaf area by

removing old leaves in tomatoes resulted in a 30 percent reduction in transpiration with no detrimental effect on crop yields (Adams *et al.*, 2002).

Crop-based environmental control

Operational control should not aim at individual environmental factors (temperature, humidity, CO₂) but at energy-efficient crop production and quality control, taking into account the impact of control actions on both crop production and energy consumption. While this (model-based) approach has been under research since the early 1980s, its practical application in on-line control of greenhouses remains limited because it requires the end-user to adopt an entirely new approach and abandon current practices.

FIGURE 4
Relation between yearly evaporation and energy use for a traditionally grown tomato crop under northwestern European conditions



Climate control – GAP recommendations

- Carry out regular maintenance; check and calibrate devices, sensors, pumps, valves, ventilators etc. no less than at the start of each cropping period.
- Do not place thermostats/sensors in direct sunlight; use aspirated sensors.
- Optimize incoming solar energy in cold conditions by delaying ventilation or opening of thermal screens.
- Use greater differences between day and night temperature settings for ventilation (4–6 °C); adopt automatic temperature integration if available.
- Monitor settings of environmental control system or thermostats; check regularly that they are in line with the production strategy.
- Consider use of higher humidity setpoints during periods with lower irradiation in heated greenhouses.
- When using a thermal screen, first open the screen (rather than the vents) to reduce humidity.
- When available, apply CO₂ at least to ambient concentration (i.e. 340–370 µmol mol⁻¹); it does not reduce energy use but significantly contributes to crop growth and production.

Rational energy use in practice

While the introduction of new innovative environmental control technologies will increase energy efficiency, major advances can be made by improving the hardware design of heating and ventilation systems and increasing the accuracy and the frequency of controls of the sensor network. Thus, the major practical recommendations for rational energy use largely depend on the grower’s operational control of the available hardware in terms of heating, ventilation and cooling systems, screens etc.

Energy saving: reduction of greenhouse energy requirement

Covering materials and screens

Most energy loss in natural ventilated greenhouses occurs through:

- convection and radiation from the greenhouse cover; and
- sensible and latent heat transfer through ventilation.

Improved insulation and reduced ventilation are therefore the first steps towards creating energy-conserving greenhouses. The basis of energy reduction is good maintenance of greenhouse hardware (doors, cover, sidewalls, foundation). Measures must be taken to prevent unnecessary air leakage from the greenhouse: keeping greenhouse doors closed, sealing air leakages, repair of broken cover material and sidewalls, and uniform closure of natural ventilators.

Increasing the insulation value of the greenhouse has a major impact on energy consumption as most energy loss takes place through the cover. Therefore different technologies can be applied, including increase of the insulation value using double or triple layer materials and application of coatings to reduce radiation loss. A combination of these techniques may lead to a significant reduction in energy use for the entire greenhouse system (Table 2).

TABLE 2
Effects of different types of greenhouse covering materials on annual energy use of year-round tomato crop

Greenhouse cover	(Fossil) energy use (m ³ natural gas/m ²) ^a	
Single glass	53	(100%)
Single glass with screen	40	(75%)
Double cover	40	(75%)
Double with screen	33	(62%)
Double with low emission	28	(53%)
Three-layer with low emission	26	(49%)

^a 1 m³ natural gas equivalent to approx. 31.5 MJ.
Bot *et al.*, 2005

However, a major disadvantage of most insulating covers is the reduction in light transmission and increased humidity. In practice, the potential energy saving of double and triple covering materials is rarely achieved, since the grower will try to compensate for the higher humidity levels by increasing the dehumidification of the greenhouse environment.

For energy conservative (film) greenhouses, materials combining high light transmission with low IR transmission are preferred (Hemming, 2005). PE and EVA films generally have high IR transmission

rates which makes them less suitable when designing energy-efficient greenhouses (Table 3).

Screens

A thermal screen adds an additional barrier between the greenhouse and its surroundings and reduces both convection and ventilation loss. Screens can be either fixed or movable. Fixed screens are normally used during the early growth stage and production period of the crop, but the constant reduction of the light level and increased humidity limit the period of application and consequently the potential energy saving.

Movable screens have less impact on light transmission than fixed screens or double covering materials. Screens may reduce energy use by more than 35–40 percent, depending on the material (Table 4). In practice, movable screens are closed for only part of the entire 24-hour period depending on the grower's criteria for opening and closing, which are generally related to humidity and light levels. In commercial practice, this results in energy savings of about 20 percent in

TABLE 3
Visible light transmission (diffuse) and IR transmission of different greenhouse covers

Material	Thickness	Light transmission	IR transmission
"Standard" glass	4mm	82%	0
Hard glass	4mm	82%	0
Anti-reflection glass	4mm	ca.89%	0
PE film	200µm	ca.81%	40–60%
EVA film	180µm	ca.82%	20–40%
ETFE membrane	100µm	88%	15–20%
Polycarbonate (2-layer)	12mm	61%	0
PMMA (2-layer)	16mm	76%	0
Polycarbonate zigzag	25mm	80%	0

TABLE 4
Greenhouse screen materials and their characteristics

Type	Transmission in direct light	Transmission in diffuse light	Energy saving
ILS 10 Revolux	71	65	45
ILS 50 Revolux	44	40	20
ILS Clear	83	77	47
XLS 10 Revolux	87	80	47
XLS 15 Firebreak	50	47	25
XLS 16 Firebreak	39	37	20

Svensson, Sweden

northwest Europe. For southern regions the application of screens (and energy-saving covering material) may be less economically feasible. Due to the general lower energy use (see Figure 4) the financial benefits of savings will be less while investments remain relatively high.

Energy-efficient cooling

Ventilation

In almost all regions worldwide, and especially at southern latitudes, there is a large surplus of solar energy requiring efficient cooling systems to reduce the air temperature. Natural ventilation is the most common method of cooling, and optimizing the geometry of the greenhouse can enhance natural ventilation. With a roof slope of up to 30°, the ventilation rate significantly increases and traditional horizontal roof greenhouses are replaced with symmetrical or asymmetrical greenhouses. Windward ventilation is more efficient than leeward ventilation, so new greenhouse constructions have larger openings facing the prevailing winds.

Shading

Shading to reduce the solar energy flux into the greenhouse during periods with an excessive radiation level is a common way of achieving passive cooling. Mobile shading systems mounted inside or outside have a number of advantages, such as the improvement of temperature and humidity, quality (e.g. reduction of blossom end rot in tomato crops) and a clear increase in water-use efficiency. In southern regions in particular, movable and external shading are very efficient at improving energy efficiency.

Specific materials which absorb or reflect different wavelengths or contain interference or photo or thermochromic pigments may be used to bring down the heat load but mostly these materials also reduce the PAR level. Materials reflecting part of the sun's energy not necessary for plant growth (near-infrared, NIR) show promising results (e.g. Garcíá-Alonso *et al.*, 2006) and may be applied either as greenhouse cover or as screen material.

Mechanical cooling

Mechanical cooling (fans, heat pumps and heat exchangers) can maintain the same greenhouse temperature as does natural ventilation; it can further reduce the temperature, especially under high ambient temperatures or high radiation levels. With high cooling capacity it is possible to keep the greenhouse completely closed, even at maximum radiation levels. However, all practical and experimental experience shows that return on investment for these systems is poor for all regions in the world, except for direct evaporative cooling by fogging/misting and indirect evaporative cooling (pad and fan).

This is most likely the result of the positive effects of lower temperature and higher humidity resulting in better growth and production, at least with major

fruit and vegetables. Therefore, direct evaporative cooling by misting and pad and fan cooling still gives the best economic results and increases energy efficiency primarily through the impact on production.

Energy reduction in practice

The reduction of the energy requirement is related to the grower's strategic choices in relation to greenhouse construction, covering material and environmental equipment in terms of heating system, ventilation, cooling, screens etc. Increased investment is required and needs to be considered in terms of return on investments.

Energy efficiency – GAP recommendations

- Take care of regular maintenance of the greenhouse hardware (doors, cover, sidewalls, foundation, ventilators, pad/fan, screen material etc.).
- Keep doors closed, seal air leakages, replace broken cover material and ripped screens.
- Select greenhouse cover materials with low IR transmission.
- Use (moveable) thermal screens for areas with low average or low night temperatures.
- Use thermal screens in particular in locations characterized by clear sky to reduce radiative heat exchange with the sky canopy.
- Replace horizontal roof greenhouses with symmetrical or asymmetrical greenhouses with roof slopes up to 30°.
- When using natural ventilation, build greenhouses with large windward ventilation openings located in line with the prevailing wind direction.
- If cooling is required, use misting or pad and fan cooling; if not sufficient, add a shading screen.
- Replace old greenhouses with newer more energy-efficient models.

Replacement of fossil fuel by other sustainable sources

As CO₂ emission is directly related to the use of fossil fuels for heating and cooling greenhouses, alternatives (e.g. solar and geothermal energy, biomass and waste heat) can significantly help achieve the reduced CO₂ emission targets. Using waste heat and CO₂ supply from combined heat and power generators (CHP) and feeding the electricity to the national grid can save a significant fraction of fossil fuel. While energy is not directly saved at greenhouse level, CHP reduces CO₂ emission at national level by reducing the CO₂ emission of the central power plants.

However, the economically feasible application of CHP largely depends on the local situation. Sometimes it is not allowed or is not technically feasible to feed electricity into the national grid, or the price of electricity is (too) low. Stand-alone use of CHP (for electricity used at greenhouse farm level) is only an option

in large-scale greenhouses and requires solutions for the imbalance between the not-synchronized heat and power use at farm level, for example, using heat storage systems.

Biomass and anaerobic digestion are good alternatives for fossil fuel but the availability and massive quantities needed and uncertainty about the energy content are major drawbacks for large-scale application. For example, a 1-MW biomass source may require up to 2 500 tonnes of dry mass per year. This not only requires significant investments but also logistic solutions and the availability of this biomass in the surrounding area. Furthermore, the continuity of the biomass supply may be a problem as the storage of required amounts of gas is almost impossible. With regard to CO₂ from this gas, special attention should be paid to pollution aspects after burning components like SO₂/SO₃ and NO_x may seriously damage the crop. However, for small-scale application and stand-alone greenhouses without connection to energy infrastructure, it may be a valid option.

Depending on the geology of the area, geothermal energy (water temperatures > 60 °C) is a promising alternative. Large (volcanic) areas in the world (e.g. Turkey) have geothermal potential which can be economically feasible for greenhouse heating but so far the number of geothermal heated greenhouses is limited, primarily because of the high financial risks related to drilling the hot water well. In the Netherlands a geothermal source (water 65 °C, depth 1 700 m) for greenhouse heating required an investment of about € 5.5 million (price level 2007). The total costs, however, can differ greatly as in other areas of the world geothermal energy is available at lesser depths. For the economic application of deep geothermal energy, in general a large greenhouse area (> 20 ha) has to be connected to the source.

Sustainable energy resources – GAP recommendations

The use of alternative energy sources depends on the strategic and long-term choices of the grower and usually becomes relevant if previous steps have led to a reduction in the required energy input per unit of area. Although all previous recommendations also have to be considered from the point of view of economic feasibility, this last step requires specific attention to risk analysis concerning the reliability of availability/delivery of the alternative source and its price fluctuations since in general the investment costs related to this step are generally (very) high. For economic reasons (economy of scale), application of more sustainable energy sources generally requires connection to a large greenhouse area. It is therefore recommended to use specialized consultants and advisory services when considering the use of these sustainable energy sources.

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5. Choice of species and cultivars for protected cultivation

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INTRODUCTION

The choice of species and cultivars for greenhouse production should not rely on single farmer initiatives, but should be the outcome of a coordinated programme that, for a given area, takes into consideration agro-environmental constraints, technology development and socio-economic opportunities.

The choice of species and cultivars for protected cultivation is a fundamental variable that may significantly affect the success and economic return of the entire production process (La Malfa and Leonardi, 2001). Good agricultural practices in greenhouse cultivations include the choice of genotypes best suited to a specific agricultural context; however, the process is complex, with a wide variety of solutions to be considered.

In intensive production systems, such as greenhouse cultivations, before selecting the most suitable species or cultivar, some fundamental questions need to be answered:

- What to produce
- When to produce
- How to produce
- Where to sell the product

There are two basic options available to farmers:

- Choose a species for its high economic potential and develop the most suitable protection, growing systems and technology.
- Choose a crop suitable for existing structures within the farm and capitalize on those.

The market is, in most cases, the limiting factor in intensive year-round productions: high yields may be obtained with optimal control of the climatic conditions in a greenhouse, but they may not meet market requirements (offer does not match demand). Although economic factors (markets) and political decisions (subsidies for certain crops in specific areas) may have a substantial impact on crop choice, the focus herein is on the options for specific greenhouse agrosystems, often closely linked to the agro-environmental constraints. Cultivar choice also depends on the type of farm: medium- and large-scale farms may sell their products in national and international markets, while small-scale farms produce to fulfil the family's needs or for limited profits in local markets.

Compared with open-field cultivations, greenhouse technologies enable the cultivation of a large number of species in a specific geographic area since they reproduce, in a controlled environment, climatic conditions optimal for certain species, regardless of the external environment. The cost/benefit ratio is a major factor determining the level of technology implemented in greenhouse systems which indirectly reflects the current geographical distribution of greenhouse typologies: more isolated (heated, closed and semi-closed) in central/northern Europe; less isolated (cold, open or semi-open) in southern Europe and the Mediterranean. This is an important consideration when choosing crops and cultivars since, for the same species, different cultivars may adapt well to specific cultural conditions and protected environments.

While cut flowers, ornamentals and fruit crops may be important under protected cultivation, this chapter concentrates on vegetable crops, including new crops and product diversification, given that the crops currently grown tend to be limited to a relatively small number of species and cultivars.

CHOICE OF THE CROP

Under mild winter climatic conditions, cold greenhouses and protected cultivations concentrate on vegetable productions belonging to the Solanaceae (tomato, pepper, eggplant) and Cucurbitaceae (melon, summer squash, watermelon, cucumber) families. These crops (accounting for > 80% of the protected area in most Mediterranean countries) suit cold greenhouse conditions and meet local market requirements. Their success in protected cultivation is due to:

- wide consumption;
- good adaption to unsteady climatic conditions inside cold greenhouses as a result of the crops' indeterminate growth habits; and
- long cultivation cycles (more continuous use of greenhouses during the year).

Leafy determinate plants, on the other hand, do not share the above characteristics, and may therefore encounter problems related to bolting control, with effects on yield and product quality.

From an economic point of view, it should be noted that greenhouse vegetable productions in Mediterranean areas are constantly increasing (Tuzel and Leonardi, 2009), while growers' incomes are decreasing, despite efforts to lower production costs and improve competitiveness (La Malfa and Leonardi, 2001). Crop choice may become increasingly important to preserve the economic sustainability of the established greenhouse industry and improve the performance of farms introducing protected cultivations in new areas.

Crop choice must consider species and genotypes capable of providing specific produce typologies, taking account of market and economic conditions, crop characteristics and requirements, compatibility between crop and microclimate, and soil characteristics and soil-borne diseases, more specifically:

- market requirements
- economic convenience
- economic and social context
- distance from markets
- plant dimensions
- crop requirements
- labour requirements
- climatic conditions
- characteristics of protection means
- possibility of active climate control
- soil characteristics and soil-borne diseases

Market demand for a specific product is the main prerequisite, with a distinction between widespread greenhouse crops and other minor crops (speciality crops, e.g. squash flowers, or locally consumed products, e.g. gombo). In all cases, considering the increasing production costs and the short shelf-life of vegetable products, crop choice should guarantee an optimal match between production and timing of delivery to the market.

The economic considerations concern the relationship between market prices and farmers' returns. Production costs are not fixed: for example, labour in Mediterranean countries can vary from a factor of 1 to 8. Fertilizers, pesticides and transportation also vary enormously in cost. When farmers intend to produce for local markets, it may be possible to reduce transportation costs adopting alternative solutions such as pick-your-own, roadside markets or arrangements with local grocery stores. However, these systems are not common in greenhouse cultivation, which mostly relies on centralized market distribution or arrangements with supermarkets and supermarket chains. The availability of cold storage rooms on the farm (or close by) is useful – even critical – for preserving the quality of perishable products before transportation.

In addition to the physical compatibility between crop and shelter (e.g. tunnel size and height of vertically trained plants), there are other specific crop requirements to be considered. In general, the greater the climatic requirements, the lower the compatibility with the protective shelters most utilized in mild winter climates. The labour requirements, as well as labour availability during the growing cycle, should be considered. In particular in small (family) farms, the time and labour required for a specific crop should not be underestimated, and, if possible, the requirement should be calculated in advance. Furthermore, some tasks may require different levels of specialization requiring additional investments in training or technological equipment (e.g. fertigation units for hydroponic systems).

With regard to the external conditions, protected cultivation can be in a wide variety of situations. Greenhouses are located in different climates, however with a higher concentration in areas where the winter is mild and places where climatic risks are low; but there has been expansion to areas with significant climatic risks. Moreover, under protected cultivation in mild winter climates, the greenhouse building characteristics and the frequent total absence of active climate control have a major effect on the microclimate (Baille, 2001). Therefore, when farmers rely on very simple structures for crop protection, it is essential to choose a species that suits the specific climatic conditions while having moderate control of the growth environment (e.g. tomato vs pepper).

CHOICE OF THE CULTIVAR

Greenhouse production is a very dynamic economic sector and must cope with rapid changes in market trends and consumer preferences. Consequently, choosing the right cultivar in greenhouse production is a critical stage in the production process (Tuzel and Leonardi, 2009). Cultivar choice is important for each crop and specific produce typology. Cultivars which produce fruits with varying characteristics are not valid alternatives in the greenhouse production system which must respond to strict production and market requirements.

Cultivars for protected cultivation differ quite substantially from those used in open-field vegetable productions: they are less exposed to environmental constraints and consequently can better express their yield potential. However, different cultivar-specific requirements may also exist depending on the level of technology used in protected cultivation (e.g. cultivars adapted for long-cycle crops).

In the past, production strategies in Mediterranean greenhouses have been based on adapting crops to a suboptimal environment due to limited greenhouse climate control. Over the years greenhouse climate control systems have been developed, resulting in greatly improved yield and product quality (Castilla *et al.*, 2004).

A range of factors may condition the choice of one cultivar over another and growers, traders and consumers have different perspectives. For example, for growers, potential yield, extended harvesting time with constant product quality, and resistance to biotic and abiotic stresses are major considerations.

Cultivars resistant to major pathogens and pests have been introduced in protected cultivation and increasingly represent an important component of the production process (Tuzel and Leonardi, 2009). The introduction of stress-tolerant cultivars allows a significant reduction in chemical treatments, environmental pollution and production costs, while providing new possibilities for the implementation of integrated cultivation processes and greenhouse organic productions. However, when adopting resistant cultivars, it is necessary to consider the stability of the specific resistance under different microclimatic and agronomic conditions. With particular fruit typologies (e.g. local cultivars), resistance to soil-borne diseases is not a necessary requirement, since it can be overcome by using suitable rootstocks and well-developed grafting techniques; the genotype should be chosen together with a suitable rootstock (with specific resistance and high affinity with the scion) (Leonardi and Romano, 2004).

For the trader, long shelf-life and any characteristic that makes the product unique and highly appreciated (hence, requested) by consumers are important factors. For the consumer, the product must be easy-to-use, versatile, with good taste and health properties.

Cultivar choice should theoretically take into account all the above aspects, but in practice, different priorities are defined by growers in relation to product destination and specific market targets.

It is important to choose cultivars that in specific areas may valorize the environmental conditions and technical factors involved in the production process. Recent advancement due to rapidly developing breeding technologies has led to a substantially broader portfolio of new cultivars with genetic traits for improved disease resistance, adaptability to suboptimal temperature and light, and other specific traits, such as parthenocarpy and suitability for grafting. In addition to standard quality parameters (size, colour, Brix, % dry matter, shelf-life etc.), particular attention has been given to qualitative traits defining the nutritional profile of fresh fruits and vegetables (Lenucci *et al.*, 2006).

While the above-mentioned traits are all important in greenhouse production, it is fundamental to assess their responsiveness under different conditions in the specific growing area. This is not an easy task since the high renovation rate of the available cultivars and the lack of systematic experimentation of agronomic performances mean that there are no reliable data to provide useful information to the farmers.

Given the multiple qualities a cultivar is expected to have, seed and breeding companies strive to respond to market requirements and broaden the portfolio of cultivars. In addition, there are legal, regulatory and certification requirements with regard to product quality and safety, as well as restrictions on chemicals used in agricultural production (Leonardi, 2005), all of which increase the pressure for the selection of high quality cultivars capable of tolerating most common greenhouse pests and diseases. At the same time, seed companies tend to impose their selections on the market with a consequent reduction in germplasm diversity and unavoidable loss of important and valuable genetic traits. Systematic coordinated breeding programmes to preserve local genetic resources adapted to specific environments are needed to capitalize on, valorize and maintain biodiversity.

It is important to develop, in a representative greenhouse area, a local screening programme to evaluate and assess recently released cultivars (with the support of local administrations and research institutions), in order to assist farmers and endorse the innovation of vegetable cultivars in parallel with standard activities developed by seed and breeding companies (Williams and Roberts, 2002). An extension programme of this kind should also provide technical advice to farmers on cultural aspects to reach the yield and quality potential of specific species. The feed-forward-feed-back loop between farmers, extension services and seed companies may generate an effective system to preserve and valorize underexploited genetic resources.

TRADITIONAL VERSUS INNOVATIVE GREENHOUSE PRODUCTIONS

In greenhouse cultivations, more than in other agrosystems, there is increasing interest in crop diversification with a view to preserving the economic sustainability of the established greenhouse industry and improving the performance of farmers who have introduced protected cultivations in new areas (La Malfa and Leonardi, 1993).

The identification of new crops for introduction into farming systems is an important aspect of the economic sustainability of protected cultivations. In addition to the fundamental requisites of adaptation to cold greenhouse conditions, they should guarantee an economic return, which must be competitive with that obtained with other crops.

Results from an EU research project in the 1990s, involving several European countries, highlighted the potential of some speciality crops (La Malfa *et al.*, 1996), including crops grown on small acreage, ethnic vegetables, gourmet vegetables, miniature vegetables and vegetables absent or rare in certain areas (Table 1). The importance of speciality vegetables has increased substantially in recent years (Maynard, 2002).

TABLE 1

Some of the new crops exploited in cold greenhouses in the Mediterranean area: global scoring of crops and some of the main traits relative to the plant or to the product as recorded in cold greenhouse cultivation

Crops	Scoring	Traits
Asparagus	**	Short rest period; earliness; spear quality
Asparagus lettuce	*	Shortness of cycle; fibre content of the stem; low success rate with consumers
Bottle gourd	***	Bulky plant; difficulties in crop management; fruit well accepted
Carosello	*	Disease susceptibility; earliness; irregular shape and size of fruits; good taste
Chinese cabbage	***	Bolting, shortness of cycle; good taste; product well accepted
Okra	*	Low harvest index; frost susceptibility; narrow market; low productive level
Orach	***	High yield level; short shelf-life; good taste
Pak choi	**	Bolting; high yield level; high fibre content
Parthenocarpic tomato and eggplant	***	Setting at low temperature; irregular fruit shape and size
Radish	**	Shortness of cycle; cracking of the roots; frequent pungency taste
Rocket	**	Shortness of cycle; bolting; low fibre content
Snake melon	***	Earliness; irregular fruit; no bitter taste
Sweet corn	***	Irregular setting; bulky plant
<i>Vigna</i> spp.	**	High cost of harvesting; short shelf-life
Water spinach	**	Frost damage; high growth rate, good taste
Wild beet	***	High-yielding; high mineral and vitamin content
Wild borage	*	High growth rate; high mineral and vitamin content
Wild cabbage	*	Bolting; high growth rate; high mineral and vitamin content
Wild chicory	*	Slow growth rate; resistance to bolting; satisfactory yield level and quality

* = poor; ** = fair; *** = good.

La Malfa *et al.*, 1996 (adapted and updated)

There are other new crops (e.g. okra, orach, rocket, asparagus, lettuce) which give satisfactory agronomic results but market demand remains somewhat limited. The most significant example of diversification paradoxically concerns a well-established crop: tomato (La Malfa *et al.*, 1996). By capitalizing on its genetic intraspecific diversity, new crops have been established in recent decades to produce new fruit typologies. In Italy, cherry and cluster tomatoes were quite rare 20 years ago and now represent more than 50 percent of greenhouse production.

Crop diversification, obtained by growing new species or varieties and in some cases new cultivars, is important for the sustainability of the entire production process. The introduction of new crops could compensate product losses resulting from unexpected biotic or abiotic stresses, or from market fluctuations, and enhances overall agrosystem stability. An increasingly important issue in this respect is the use of transgenic cultivars capable of adding valuable traits to greenhouse crops. Although still under debate, the use of transgene technology

in agriculture to improve the environmental sustainability of the production process is common practice in many countries and could be accepted in the future in Europe. However, it is unlikely that crop diversification in Mediterranean cold greenhouses will reach the level of heated greenhouses. Leaving aside the economic factor, a heated greenhouse can be climatically adapted to nearly any plant requirement, while in unheated greenhouses, plants must adapt to an internal environment which depends on the external climatic conditions.

Considering only the biological requirements of new crops, cold greenhouses should be used for mesophytic plants (La Malfa and Leonardi, 2001). The photothermic requirements of these species should not be too high, so they can be met through simple modifications of internal microclimatic conditions; however, they should not be so low that they reduce or nullify the advantages of the greenhouse environment in terms of productivity, quality and harvest period. For these environments, new crops have to withstand widely variable thermal ranges on a daily and seasonal basis. The minimum and maximum temperature levels reached daily in these areas are often outside the thermokinetic window, i.e. the thermal interval suitable for biological processes. Moreover, this interval is not always well known for new candidate crops.

A greenhouse should produce the maximum favourable effects on plants with a long cycle and indefinite growth, in order to achieve more intensive greenhouse utilization. In addition to the plant characteristics, other factors are considered when choosing new crops: organizational aspects (e.g. using the greenhouse also during summer rest periods) and marketing reasons (e.g. improving quality or extending the supply period). Diversification in a cold greenhouse is, therefore, rather limited despite the high interspecific and intraspecific variability of vegetable plants (hundreds of species in the Mediterranean Basin alone).

On the basis of this analysis, it can be concluded that the requisites of a candidate new crop for Mediterranean cold greenhouses differ in terms of shelter typology. In contrast, in the Netherlands, for heated greenhouses, the principal requisites for new crops are: year-round cultivation, adaptation to soilless culture and to heating, high yield potential, low labour requirements, high thermal requirements (making open-air cultivation impossible) and high quality compared with open-air products. All other considerations – production costs, product quality, and overlapping with other open-air crops in the production calendar – are valid for heated and unheated greenhouses.

At global level, more than 1 000 species are consumed as “vegetables”. There are several sources of new crops introduced in greenhouse productions:

- species introduced from other countries;
- minor species and varieties cultivated in the past, and now overlooked or not systematically cultivated;

**Plate 1**

Innovative and traditional products

- cultivars of species already widely cultivated in greenhouses but capable of supplying vegetables with new characteristics;
- species to date cultivated only in the open air; and
- wild species, eaten as vegetables.

In summary new crops should:

- adapt to agroclimatic and social conditions;
- meet consumer requirements; and
- be marketable and profitable.

Innovative crops allied to traditional ones and capable of producing new vegetable typologies include: cherry tomato (20 years ago), beef tomato (recently), immature pea pods, small eggplants, small peppers, small strawberries, yellow and variegated green bean pods and yellow courgettes. These should be considered new to certain areas (in the Mediterranean), although they may already be well known elsewhere.

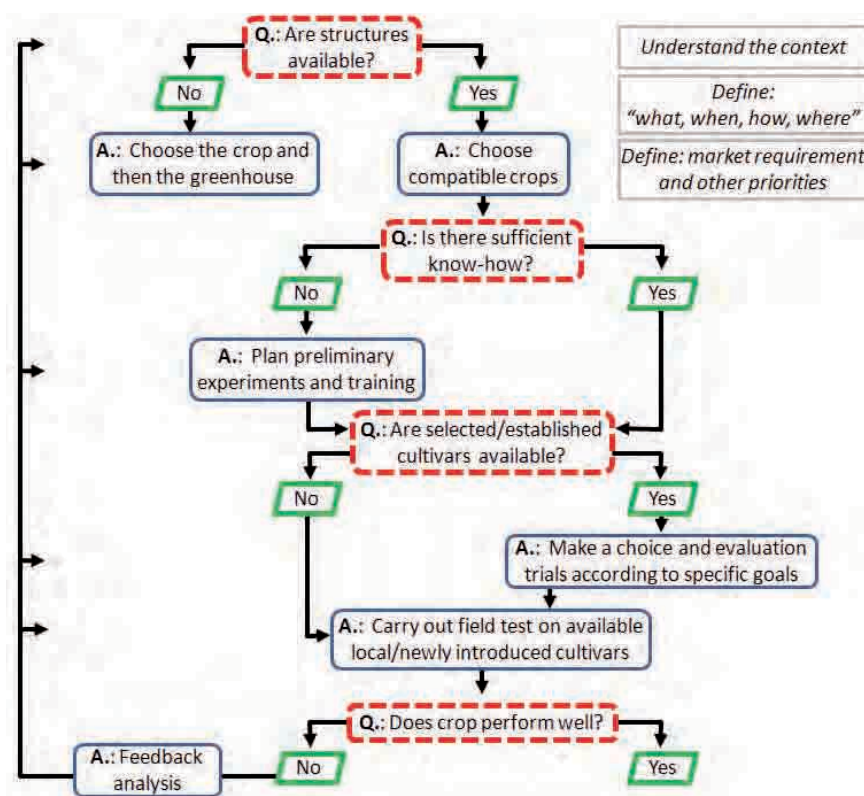
The market is certainly a major driving factor for the introduction of a new crop. Seedless watermelons have been a successful innovation with widespread consumption. In other cases, a particular product, such as gombo (*Abelmoscus esculentum*), may not be widely distributed, but it responds to a very specific consumer demand (in this case from Asia and Africa).

The potential of new crops depends on the market opportunities. Diversification could therefore be aimed at producing relatively small quantities of a particular product if it is targeted towards a specific market. Unfortunately, there is not sufficient monitoring and information on new crops introduced in standard greenhouse farming systems to compile a database to be used as a guideline. This also hinders further expansion of these crops and possible developments of up-to-date cultural techniques.

CONCLUSION

The choice of species and cultivar is an important factor for determining the sustainability of protected cultivations. While the selection process is complex, some of the main aspects may be simplified (Figure 1). The choice is based on a step-by-step approach preceded by a specific analysis aimed at understanding the demand and priorities. This approach is based on the awareness of available know-how and on the possibility of carrying out experimental activities; thanks to a feedback analysis, it is to be considered dynamic and therefore adaptable to the continuous evolution of social, economic and agronomic conditions.

FIGURE 1
Simplified flow chart summarizing the main steps for the choice of species and cultivar for protected cultivation



GAP recommendations

- Take into consideration the general agro-environmental criteria for choosing species and cultivars in a given environment. These include species-specific physiological needs in terms of light, temperature, humidity and soil characteristics.
- Validate the specific choice of crops and cultivars in the economic context.
- Organize specific training programmes to extend knowledge of agro-techniques specific to certain crops.
- Develop technical training in parallel with micro-economy training to implement socio-economic variables and market trends in the overall assessment of economic convenience.
- Consider the advantages and disadvantages of diversification compared with specialization on a case-by-case basis.
- Adopt a coordinated programme for crop diversification and introduction of new species or cultivars, to valorize and capitalize on available labour, technical specialization, environmental parameters and socio-economic constraints in a specific area (avoid initiatives by single growers).
- Although greenhouse cultivation is flexible, take into account for the overall farm economy that the introduction of new crops requires time to put in place the fully operative pipeline from production to consumption.
- Do not limit a cost-benefit analysis to agronomic evaluation; socio-economic parameters and time are critical variables.
- To implement these fundamental principles, a systematic approach based on the involvement of different actors is necessary for an effective and successful decision process.

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6. Water requirements and irrigation management in Mediterranean greenhouses: the case of the southeast coast of Spain

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INTRODUCTION

Large areas of unheated greenhouses are located in the coastal regions of the Mediterranean Basin (Pardossi *et al.*, 2004). These are generally relatively low-cost structures covered with plastic, without active climatic control systems, in which drip irrigation is used with soil-grown or substrate-grown crops (Castilla *et al.*, 2004; Pardossi *et al.*, 2004; Castilla and Hernández, 2005). These relatively simple greenhouses are known collectively as Mediterranean greenhouses, and they are most commonly used for vegetable crop production. Characterization of the greenhouses, growing conditions, vegetable species grown and management practices have been reported (Castilla *et al.*, 2004; Pardossi *et al.*, 2004; Castilla and Hernández, 2005). The largest area of Mediterranean greenhouses is located on the southeast (SE) coast of Spain; the major cropping cycles in this region and the crops grown are presented in Table 1.

TABLE 1
Major cropping cycles and the vegetable species grown in Mediterranean greenhouses in Almería, SE Spain

Major cycles	Typical period of cycle	Crops grown
Autumn–spring	August–May	Tomato, eggplant
Summer/autumn–winter	July/Aug./Sept.–Jan./Feb.	Pepper, tomato, cucumber, zucchini
Spring–summer	Jan./Feb./Mar.–May/June	Melon, ^a watermelon, ^a tomato, cucumber, zucchini

^a Cooling with whitewash not used during warm periods with these species.

**Plate 1**

Aerial view of plastic greenhouses in Almería, Spain

In these generally dry Mediterranean regions, water is relatively scarce and is often subject to increasing competition from housing and tourism. Also, local water resources are often detrimentally affected by irrigated greenhouse horticulture which causes various problems, including overexploitation, nitrate contamination and salinization of aquifers. Consequently, there is considerable and increasing pressure to optimize irrigation management and ensure optimal production and economic returns, and to avoid environmentally harmful excessive irrigation applications.

Five aspects of irrigation of vegetable crops in Mediterranean greenhouses are covered herein:

- crop water requirements
- characterization of the amounts of water used and current irrigation practices
- irrigation scheduling of soil-grown crops
- irrigation scheduling of substrate-grown crops
- water-use efficiency

Much of the data presented are from SE Spain, which has the largest greenhouse area dedicated to intensive vegetable production in the Mediterranean Basin and one of the highest concentrations of greenhouses in the world. A considerable amount of scientific and technical information has been produced in this region during the last 15 years regarding water use and irrigation management of greenhouse-grown vegetable crops. This section focuses on soil-grown crops, while irrigation in substrate-grown crops is considered in a more general manner.

**Plate 2**

Examples of plastic greenhouses in Almería



WATER REQUIREMENTS OF MEDITERRANEAN GREENHOUSE CROPS

Components of crop water requirements within greenhouses

Crop water requirement is the total volume of water that a crop needs to maintain maximum rates of crop evapotranspiration (ET_c); it is calculated as the difference between ET_c and water obtained from rainfall and soil water. Technically, the water required to maintain ET_c is the “net” crop water requirement, with the “gross” crop water requirement taking into account extra irrigation to consider salinity and application uniformity. In this section, crop water requirements are “net” crop water requirements. Since no rainfall enters greenhouses and seasonal soil water extraction is negligible (Fernández *et al.*, 2005), because the soil is continuously close to field capacity from high frequency drip irrigation, it can generally be assumed that the crop water requirement of greenhouse-grown crops is equivalent to ET_c.

Crop evapotranspiration of Mediterranean greenhouse crops

The ET_c of major vegetable crops grown in soil in unheated plastic greenhouses in the Mediterranean Basin has been determined (Table 2). Many of these data were obtained using drainage lysimeters in Almería, SE Spain (e.g. Orgaz *et al.*, 2005). Seasonal crop water requirements (i.e. ET_c) determined in Almería range from 170 to 371 mm (Table 2). The lowest values are generally for spring-grown melon and watermelon crops with 3–4-month growing periods, and the highest values for pepper crops with a growing season from September to late May. Reported ET_c values for soil-grown tomato, one of the most important greenhouse crops, range from 231 mm for a spring cycle to 260 mm for an August–

TABLE 2

Net crop water requirements (ET_c) determined experimentally for vegetable crops grown in soil and substrate in greenhouses in the Mediterranean Basin

Species/ management	Crop cycle (no. days)	ET _c (mm)	Reference
<i>Crops grown in soil</i>			
Sweet pepper	Sept.–May (258)	371	Orgaz <i>et al.</i> , 2005
Sweet pepper	July–Feb. (198)	218	Gimenez <i>et al.</i> , 2012
Tomato	Aug.–Jan. (172)	260	Gallardo (unpublished)
Tomato	Mar.–July (122)	231	Gallardo (unpublished)
Melon (not supported)	Jan.–June (135)	219	Orgaz <i>et al.</i> , 2005
Melon (supported)	Mar.–June (90)	177	Orgaz <i>et al.</i> , 2005
Watermelon	Mar.–June (90)	170	Orgaz <i>et al.</i> , 2005
<i>Crops grown in substrate</i>			
Sweet pepper	July–Jan. (183)	308	Rodríguez, 2008
Tomato	Sept.–Mar. (162)	177	Gallardo <i>et al.</i> , 2009
Tomato	Mar.–July (119)	276	Gallardo <i>et al.</i> , 2009
Melon (supported)	Feb.–June (119)	186	Rodríguez, 2008

**Plate 3**

Crops grown in greenhouses in Almería: pepper grown in soil (left) and tomato grown in substrate (right) (note the tall narrow canopies due to crops being vertically supported and pruned)

January cycle (Table 2). The ET_c values for substrate-grown crops have been calculated by subtracting drainage from irrigation volumes. Generally, these values are similar to those for equivalent crops grown in soil (Table 2). Reported ET_c values for substrate-grown crops are 177 mm for a short cycle autumn–winter tomato crop (Gallardo *et al.*, 2009), 276 mm for short-cycle spring tomato crops (Gallardo *et al.*, 2009), and 308 mm for a summer–winter sweet pepper crop (Rodríguez, 2008).

Compared with equivalent vegetable crops grown outdoors with irrigation, the seasonal ET_c of greenhouse vegetable crops

is appreciably lower due to the reduced evaporative demand inside the greenhouse (Fernández *et al.*, 2010). The evaporative demand is lower inside than outside due to the decrease in solar radiation (40% on average) and the greatly reduced wind speeds of 0.1–0.3 m s⁻¹ or less (Fernández *et al.*, 2010). The evaporative demand inside the greenhouse can be 60 percent of that outside (Fernández *et al.*, 2001; Möller and Assouline, 2007). Additionally, out-of-season vegetable crops are commonly grown in Mediterranean greenhouses during late autumn to early spring, when low evaporative demand contributes to the relatively low values for crop water requirements. In Almería, greenhouse crops are grown in mulched soils known locally as *enarenado* consisting of an 8–12 cm layer of coarse sand mulch on the soil surface (Castilla and Hernández, 2005); the sand mulch appreciably reduces direct evaporation from the soil surface, further reducing crop water use.

Crop evapotranspiration and greenhouse cooling

An additional factor contributing to relatively low ET_c values in SE Spain is whitewash (suspension of calcium carbonate), commonly applied to the greenhouse roof and walls during warmer periods (summer/early autumn to late autumn; early spring to summer) to decrease air temperature inside the greenhouse. The whitewash reduces the amount of solar radiation entering the greenhouse and therefore also the air temperature; consequently, there is a reduction in ET_c which is proportional to the thickness of applied whitewash. The transmissivity to solar radiation of greenhouse plastic cladding is usually about 60%; commonly used whitewash application rates reduce this to 20–30% in July to mid-September, and to approximately 45% in mid-September to mid-October and in late February to late June. Other cooling techniques affecting ET_c , such as misting and shading screens, are currently used by only a small percentage of growers in SE Spain (Céspedes *et al.*, 2009). Values for the reduction in radiation and consequently in ET_c as a function of applied whitewash are given in Fernández *et al.* (2001).

Determination of crop evapotranspiration for Mediterranean greenhouse crops

To determine crop water requirements, the standard FAO methodology (Doorenbos and Pruitt, 1977; Allen *et al.*, 1998) has been adapted for use in vegetable crops grown in Mediterranean greenhouses in SE Spain by the Las Palmerillas Research Station of the Cajamar Caja Rural in Almería (Fernández *et al.*, 2001, 2010, 2011; Orgaz *et al.*, 2005; Bonachela *et al.*, 2006). The FAO method estimates crop evapotranspiration (ET_c) as the product of:

- reference evapotranspiration (ET_o), equivalent to the evapotranspiration of a grass crop and which quantifies the effect of climate on crop water demand; and
- the crop coefficient (K_c), which quantifies the effect of crop species and stage of development (Allen *et al.*, 1998).

Determination of reference evapotranspiration for Mediterranean greenhouse crops

Evaluation of various equations to estimate ET_o in plastic greenhouses in Mediterranean climate conditions was conducted by Fernández *et al.* (2010, 2011). A summary of the different equations, calibrated for plastic Mediterranean greenhouses, is presented in Table 3. Allen *et al.* (1998) recommend the FAO-56 Penman-Monteith method as a standard for estimating ET_o from climatic data, in both arid and humid climates, using radiation, air temperature, atmospheric humidity and wind velocity data. Inside plastic greenhouses in Mediterranean climate areas, this method accurately estimates ET_o compared with a standard grass crop when using a fixed value of aerodynamic resistance of 295 s m⁻¹ (Fernández *et al.*, 2010, 2011; Table 3).

The FAO-24 pan evaporation method (Doorenbos and Pruitt, 1977) with a K_p (pan coefficient) constant of 0.79 provides good estimates of ET_o in plastic greenhouses under Mediterranean conditions (Fernández *et al.*, 2010; Table 3). However, the pan evaporation method is not considered practical for greenhouse conditions, as it cannot be readily adjusted to consider variability between greenhouses on account of whitewashing and the age of the plastic cladding (Fernández *et al.*, 2010).

In Mediterranean greenhouses, solar radiation is the climatic parameter that most influences evaporative demand (Fernández *et al.*, 2010). In Almería, both



Plate 4

Type A evaporation tank located within a grass sward in a greenhouse

TABLE 3

Recommended equations for estimating ETo inside plastic greenhouses in Mediterranean climatic conditions

Method/ equation	Equations	Calibration values	References
Penman-Monteith	$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	$u_2=208 \cdot r_a$ $r_a=295 \text{ s m}^{-1}$	Fernández <i>et al.</i> (2010, 2011)
FAO24 Pan evaporation	$ET_o = K_p \times E_o$	$K_p=0.79$	Fernández <i>et al.</i> (2010)
Hargreaves equation	$ET_o = 0.0023 R_a \tau (T_{max} - T_{min})^{1/2} (T + 17.8)$	τ : ratio inside and outside solar radiation	Fernández <i>et al.</i> (2010, 2011)
Almeria radiation method	Julian days (JD) ≤ 220 ; $ET_o = (0.288 + 0.0019JD) R_o \tau$ Julian days (JD) > 220 ; $ET_o = 1.339 - 0.00288JD R_o \tau$		Bonachela <i>et al.</i> (2006)

Note: The equations were calibrated and tested in Almería, SE Spain.

Penman-Monteith equation:

- ETo: reference evapotranspiration (mm day⁻¹), R_n: net radiation at the crop surface (MJ m⁻² day⁻¹), G: soil heat flux density (MJ m⁻² day⁻¹) (= 0 for daily calculations), T: mean daily air temperature at 2 m height (°C), u₂: wind speed at 2 m height (m s⁻¹), e_s: saturation vapour pressure (kPa), e_a: actual vapour pressure (kPa), (e_s - e_a): saturation vapour pressure deficit (kPa), Δ: slope vapour pressure curve (kPa °C⁻¹), γ: psychrometric constant (kPa °C⁻¹), r_a: aerodynamic resistance (s m⁻¹), from FAO 56 the r_a for a grass reference surface is r_a=208/u₂

FAO24 Pan evaporation method:

- K_p: pan coefficient, E_o: pan evaporation (mm day⁻¹)

Hargreaves equation:

- R_a: extraterrestrial radiation (mm day⁻¹), τ: ratio inside and outside solar radiation, T, T_{max} and T_{min}: mean, maximum and minimum greenhouse air temperatures

Almería radiation method:

- R_o: daily solar radiation outside the greenhouse (mm day⁻¹), τ: ratio between inside and outside solar radiation (transmissivity of greenhouse cover)

the Hargreaves equation (Table 3; Doorenbos and Pruitt, 1977) and the Almería radiation model (Table 3; Fernández *et al.*, 2010) – developed for these conditions and derived from the FAO-radiation equation (Doorenbos and Pruitt, 1977) – provide accurate estimation of ETo. Given their limited climatic data requirements and relative simplicity (compared with the Penman-Monteith equation), these two methods are recommended for practical estimation of ETo in plastic greenhouses under Mediterranean climatic conditions (Fernández *et al.*, 2010).

The Almería radiation method calculates daily ETo within a greenhouse from values of the daily sum of external solar radiation and the transmissivity (the ratio between inside and outside solar radiation) of the greenhouse cladding. The value of transmissivity depends on greenhouse construction (characteristics of plastic cladding, structure) and management practices used to reduce greenhouse temperature (Bonachela *et al.*, 2006; Fernández *et al.*, 2001, 2009, 2010). The major advantage of the Almería radiation method is that calculation of ETo – and consequently of irrigation requirements – considers relevant characteristics of individual greenhouses, including greenhouse construction (structure, cladding materials, age of plastic etc.) and practical greenhouse management (whitewashing

and use of shading materials etc.). In consideration of these factors and given its simplicity and accuracy, the Almería radiation method has been used extensively in Almería for both extension and scientific purposes.

Determination of crop coefficient values for Mediterranean greenhouse crops

Crop coefficient (K_c) values have been determined for the main greenhouse-grown vegetable crops in Almería (Fernández *et al.*, 2001; Orgaz *et al.*, 2005; Table 4). The K_c values vary according to species, development stage and crop management practices (vertically supported or not). Measured maximum K_c values for crops that are not vertically supported (melon and watermelon) were between 1 and 1.1, similar to measured values for the same crops under open field conditions (Orgaz *et al.*, 2005; Table 4). By contrast, maximum K_c values for vertically supported crops (melon, green beans, tomato and sweet pepper) varied between 1.3 and 1.6 (Table 4), i.e. higher than the values reported for equivalent open field crops (Fernández *et al.*, 2001; Orgaz *et al.*, 2005). The suggested explanation for the relatively high maximum K_c values of supported greenhouse crops is that there is more uniform light penetration within the canopies thereby providing relatively higher ET rates than for unsupported greenhouse crops and open field crops which tend to be shorter with denser canopies (Orgaz *et al.*, 2005). Uniformity of light penetration increases with the following (Orgaz *et al.*, 2005):

- tall and open structure of the supported crops
- regular pruning forming more open canopies

TABLE 4
Crop coefficient (K_c) values determined for the major greenhouse-grown vegetable species in Almería, SE Spain

Species	Initial K_c	Maximum K_c	Final K_c^a
<i>Supported crops</i>			
Sweet pepper	0.2	1.3	0.9
Tomato	0.2	1.4	1.0
Melon	0.2	1.3	1.1
Cucumber	0.2	1.2	
Eggplant	0.2	1.2	0.9
Green beans	0.2	1.4	1.2
<i>Non supported crops</i>			
Melon	0.2	1.1	1.0
Watermelon		1.1	1.0
Zucchini	0.2	1.1	

Values presented are the initial K_c value for transplanted seedlings, maximum K_c values, and final K_c values where appropriate. Values were obtained by Orgaz *et al.* (2005) and Fernández *et al.* (2001).

^a Many off-season crops are terminated for market reasons before plants age sufficiently to induce a reduction in K_c values in the latter part of the crop; in these cases final K_c equals maximum K_c .

- high leaf area indices
- high proportion of diffuse radiation inside the greenhouse

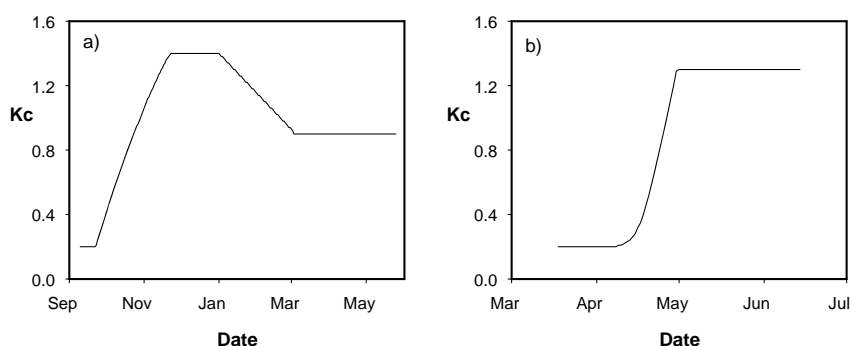
Most crops grown in greenhouses in SE Spain are transplanted. Initial K_c values for transplanted seedlings are 0.2 (Table 4). These values remain constant for a number of days and then are considered to increase linearly to maximum K_c values, maintained for variable periods. In some crops (e.g. melon, green beans) and cropping cycles, following the period of maximum K_c , K_c values can subsequently decrease slightly to lower final K_c values during the latter part of the growing season due to senescence or cold temperature damage to leaves. Many off-season crops are terminated, for market reasons (low prices), before plants are sufficiently exposed to cold temperatures to induce the reduction from maximum K_c values. For long-cycle crops grown during summer/autumn–spring cycles (e.g. pepper), the linear reduction to final K_c on account of cold temperature damage can be followed by a spring period with constant final K_c values (Orgaz *et al.*, 2005). Examples of seasonal evolution of K_c values for an autumn–summer pepper crop and a spring–summer supported melon crop are presented in Figure 1.

In the pepper crop, Figure 1a shows the four major phases referred to previously:

- linear increase from initial K_c of 0.2 to maximum K_c of 1.4
- constant maximum K_c
- linear decrease from maximum K_c to final K_c
- constant final K_c values

In the melon crop, following a period of constant initial K_c values, K_c then increased rapidly and almost linearly to reach a maximum K_c value of 1.3, which was maintained until the end of the cycle (Figure 1b).

FIGURE 1
Curves of crop coefficient (K_c) of supported sweet pepper crop (a) and supported melon crop (b)



K_c values calculated using PrHo v2.0 software, Research Station, Cajamar Foundation, Almería, Spain.

For greenhouse-grown vegetable crops, planting dates and lengths of crop cycles can vary appreciably in response to market prices, weather conditions and farm management considerations. The standard FAO method of calculating ET_c – using three constant K_c values, each for a fixed length crop stage (Allen *et al.*, 1998) – is, therefore, unsuitable for these crops. To overcome this, a model was developed that estimates K_c values as a function of thermal time inside the greenhouse (Fernández *et al.*, 2001, 2009; Orgaz *et al.*, 2005). The model, which considers greenhouse-grown vegetable crops with and without pruning, is described by Orgaz *et al.* (2005) and by Fernández *et al.* (2001, 2009).

Two approaches based on thermal time data have been developed to estimate K_c values during the crop development stage. For crops that are only slightly or not pruned, leaf area index (LAI) is estimated from thermal time, and K_c values are then determined from a linear relationship between K_c and LAI. For frequently pruned crops, an empirical linear relationship between K_c and thermal time has been determined for each species; calibration may be necessary in other environments.

Tools for calculating crop evapotranspiration of Mediterranean greenhouse crops

In Almería, the product of daily ET_o , estimated by the Almería radiation method (Fernández *et al.*, 2001, 2010; Bonachela *et al.*, 2006), and daily K_c values, estimated by the model described by Orgaz *et al.* (2005), is used to provide daily ET_c values for major vegetable crop species. Historical climatic data (Bonachela *et al.*, 2006) are used for the calculation of ET_o and K_c . As discussed above, ET_c in greenhouses may be considered equivalent to crop water requirements. The software PrHo v2.0 was developed by the Las Palmerillas Research Station of the Cajamar Caja Rural to perform these calculations under Almería conditions for major vegetable crops. A detailed description of the ET_o - K_c methodology developed by the Las Palmerillas Research Station of the Cajamar Caja Rural to calculate crop water requirements for greenhouse-grown vegetable crops in Almería is given by Fernández *et al.* (2001, in Spanish), and is available at Fundación Cajamar (2012).

The recently developed VegSyst simulation model simulates ET_c , crop growth and N uptake of greenhouse-grown vegetable crops (Gallardo *et al.*, 2011; Giménez *et al.*, in press). This model is currently being adapted as a decision support system for combined irrigation and N management in Mediterranean greenhouses (M. Gallardo, personal communication). VegSyst calculates ET_c as the product of ET_o and K_c ; ET_o is calculated using Penman-Monteith adapted to greenhouses (Fernández *et al.*, 2010, 2011), and K_c is calculated from radiation intercepted by the canopy, both estimated from climatic data inside the greenhouse (Gallardo *et al.*, 2011; Gimenez *et al.*, in press). The principal advantage of the VegSyst model is that input data are readily available climatic data: maximum and minimum daily air temperature, maximum and minimum relative humidity, daily integral of solar radiation, latitude. Historical or real time climatic data can be used.

WATER USE AND IRRIGATION MANAGEMENT

General characteristics of irrigation systems used

Irrigation management of greenhouse crops in Mediterranean areas is conditioned by the cropping media. In greenhouses in SE Spain, 80 percent of cropping is in soil and 20 percent in free-draining or “open” substrate systems, using mostly perlite and rockwool (Céspedes *et al.*, 2009). Irrigation of soil-grown greenhouse crops in this region is characterized by drip irrigation with above-ground tape; fertigation and irrigation frequencies range from daily in warm conditions to every 3–4 days in winter.

Growers’ irrigation management practices

A survey of growers’ practices reported that irrigation management (irrigation volumes and frequency) of soil-grown greenhouse crops in Almería was mostly based on the collective experience of growers and technical advisors (Thompson *et al.*, 2007a). In Almería, irrigation based on collective experience consists of fixed schedules that are adapted in response to climatic conditions and crop performance (Thompson *et al.*, 2007a).

Irrigation volumes applied by growers to greenhouse crops

A survey of total irrigation volumes (crop irrigation supply) applied to vegetable crops grown in commercial Mediterranean greenhouses in Almería was conducted by Fernández *et al.* (2007). In this study, the average irrigation supply for each of the main greenhouse crops grown in soil, with the exception of tomato, was measured during 6 years in 41 greenhouses. Applied irrigation volumes per crop ranged from 158 mm (autumn green beans) to 363 mm (autumn to spring sweet pepper), and the average value was 228 mm (Fernández *et al.*, 2007). In another crop survey in Almería, an average value of 557 mm was reported for tomato grown with an autumn to spring growing cycle (Carreño *et al.*, 2000). Reported values of total irrigation volumes applied to crops in SE Spain are presented in Table 5. In general, the surveys of commercial irrigation practices in Almería showed that crop irrigation supply increased with the length of the crop cycle, being lower for short cycle crops (e.g. 3–4 month crops of green beans, melon, cucumber and watermelon) and higher for autumn to winter and autumn to spring grown crops (5–9 months). The reported total volumes of irrigation applied per crop (Table 5) were considerably lower than for the same species grown in open field (Fernández *et al.*, 2007). This reflects the relatively lower evaporative demand inside the greenhouse and the fact that crops are often grown during periods (mid-autumn to early spring) of low evaporative demand, as mentioned previously.

Values of annual irrigation supply are higher than the crop irrigation supply since many greenhouse growers produce two crops per year. Fernández *et al.* (2007) reported maximum annual irrigation supply values of 502 mm for a sequence of autumn to winter pepper and spring melon crops. Considering

TABLE 5

Reported total volumes of irrigation applied to vegetable crops grown in soil in commercial greenhouses in Almería, SE Spain

Species ^a	Cropping cycle	Total irrigation applied to crop (mm)
<i>Individual crop cycles</i>		
Pepper ^a	Autumn–winter	311
Pepper ^a	Autumn–spring	363
Cucumber ^a	Autumn–winter	270
Green beans ^a	Autumn–winter	158
Melon ^a	Spring	177
Watermelon ^a	Spring	189
Green beans ^a	Spring	197
Tomato ^b	Autumn–spring	558
<i>Cropping seasons with two consecutive crops/seasons</i>		
Autumn–spring sweet pepper ^a		363
Sweet pepper–melon ^a		502
Sweet pepper–green beans ^a		489
Sweet pepper–watermelon ^a		465
Cucumber–melon ^a		486
Cucumber–watermelon ^a		439

^a Data from Fernández *et al.*, 2007.

^b Data from Carreño *et al.*, 2000.

greenhouses with single or double crops within a year, the average annual water supply in Almería was 444 mm for soil-grown crops (Fernández *et al.*, 2007).

The ratio of crop irrigation supply (total volume applied to a crop) to crop water requirements is known as relative irrigation supply (RIS) and is an indicator of the adequacy of irrigation practices (Fernández *et al.*, 2007). RIS values were determined for the main vegetable species in Almería by dividing crop irrigation supply values, determined in the survey, by crop water requirements calculated with the program PrHo which used the FAO approach adapted to local conditions (Fernández *et al.*, 2008, 2009). There was very large variability in RIS values between crop species and within cropping cycles for individual crops. For example, RIS values for a complete crop were 1.6 in cucumber and 1.0 in melon (Fernández *et al.*, 2007). In general, RIS values for individual crops were 2–5 during crop establishment and then progressively declined (Fernández *et al.*, 2007). The high RIS values during crop establishment reflect the practice of applying abundant irrigation to ensure the survival and establishment of transplanted plantlets or seedlings, which initially have very small root systems. Thompson *et al.* (2007a) also compared measured crop irrigation volumes with the crop water requirements calculated by PrHo; in general, the results were similar to those reported by Fernández *et al.*, (2007). Thompson *et al.* (2007a) suggested

that the high variability in RIS values between greenhouses with the same crop and the high values in certain parts of the crop cycles were evidence of the scope to improve irrigation practices and crop water use for soil-grown crops.

Additional irrigation applications

In Almería, in addition to crop irrigation, appreciable volumes of water are routinely applied to soil at other times (Thompson *et al.*, 2007a):

- between crops during summer – to disinfect soil
- pre-transplant – so that soil is moist when receiving transplanted seedlings

Soil disinfection is generally conducted every 1–2 years by applying chemical products in water, by solarization after wetting the soil profile, or by combined solarization and chemical disinfection (Céspedes *et al.*, 2009). Pre-transplant irrigations are applied prior to all transplanted crops. There are few available data of volumes of irrigation applied for soil disinfection and pre-transplant irrigations. Interviews with local technical advisers have suggested representative values of 50 and 20 mm for soil disinfection and pre-transplant irrigations, respectively (Peña, 2009; R. Thompson, University of Almería, personal communication).

Total water use associated with greenhouse cropping

A regional study (Peña, 2009) was conducted to calculate water use for the Campo de Dalías region in Almería, where 80 percent of the greenhouses in Almería are located. This study considered the following:

- water use by soil-grown crops, estimated by multiplying ET_c, calculated using the program PrHo (Fernández *et al.*, 2008, 2009), by RIS values (Fernández *et al.*, 2007);
- water use of substrate-grown crops, estimated by multiplying ET_c, calculated using the program PrHo, by 1.28, 0.28 being the average drainage fraction (they are free-draining substrate systems); and
- irrigation applied in soil disinfection and pre-transplant irrigation.

Considering all irrigation applied to crops and supplementary irrigations, the average total water use per year was 495 mm (Peña, 2009). This value does not take into account water lost from distribution systems (which can be substantial) or evaporation losses from uncovered on-farm reservoirs.

IRRIGATION SCHEDULING OF GREENHOUSE CROPS GROWN IN SOIL

Irrigation scheduling (IS) determines the volume and frequency of irrigation based on technical criteria related to crop water demand. The main approaches used for IS are:

- water balance method based on determining crop water requirements from climatic data; and
- use of soil or plant sensors.

Irrigation scheduling with climatic data

For greenhouse-grown crops, the calculation of net crop water requirement considers neither rainfall nor soil water – the latter because the soil is constantly maintained at close to field capacity. Consequently, the applied volume of a single irrigation is equivalent to the cumulative ET_c for the period between irrigations plus additional irrigation (if necessary) to consider salinity and irrigation uniformity. Procedures for determining ET_c of greenhouse-grown crops were described above. For greenhouse-grown vegetable crops receiving high frequency irrigation, irrigation frequency is usually every day under warm conditions, and every 3–4 days under cooler conditions. Soil water sensors, in particular tensiometers, are an effective method for determining frequency.

The Las Palmerillas Research Station of the Cajamar Caja Rural in Almería has developed practical extension tools for assisting farmers and advisors with irrigation scheduling of greenhouse vegetable crops grown in soil. These methods are based on determining crop water requirements, calculated as daily ET_c , using the Kc- ET_o methodology (described previously), and tensiometers are recommended to determine frequency. These tools, prepared in Spanish, comprise:

- published look-up tables; and
- computer software PrHo v2.0.

The look-up tables refer to the major vegetable species and the most common cropping periods. They are printed as a booklet distributed to growers, and can be downloaded at Fundación Cajamar (2012). They provide values of daily net crop water requirements which are values of daily historical crop evapotranspiration (ET_{c-h}), calculated using historical climatic data which are long-term average values for each day. The software PrHo v2.0 calculates daily crop water requirements for the main greenhouse vegetable crops, for cropping cycles specified by the user, using either daily historical crop evapotranspiration (ET_{c-h}) or real time crop evapotranspiration (as ET_{c-real}) calculated using real time measured climatic data (Fernández *et al.*, 2008, 2009). The PrHo v2.0 software is currently only available in Spanish; it and a user guide (Fernández *et al.*, 2008, also in Spanish) can be downloaded at Fundación Cajamar (2012).

ET_{c-h} for a given day of the year is calculated from the average daily values of:

- external solar radiation measured for that day over a 17-year period (1983–2007); and
- maximum and minimum air temperatures measured inside the greenhouse, for that day during the period 1988–2007.

ET_{c-real} is calculated from:

- actual daily values of solar radiation measured outside the greenhouse; and
- maximum and minimum daily air temperature measured inside the greenhouse for that particular day.

Within greenhouses in the relatively stable Mediterranean climate of Almería, historical ET_c (ET_c-h) calculated using long-term average climatic data has been demonstrated to be generally very similar to real time ET_c calculated using daily measured climatic data (ET_c-real) (Bonachela *et al.*, 2006). The use of historical climatic data offers considerable practical advantages over the use of real time measured climatic data. With ProHo v2.0, the relevant historical data climate values are contained within the program, whereas the real time data have to be entered each day. For the calculation of net crop water requirements (as ET_c), the PrHo v2.0 software considers the effect of whitewashing used for cooling. Following the calculation of net crop water requirements (as ET_c), the PrHo v2.0 software then calculates gross crop water requirements by considering the salinity of irrigation water and the uniformity coefficient of the irrigation system.

The look-up tables provided by the Las Palmerillas Research Station of the Cajamar Caja Rural in Almería and the PrHo v2.0 software are effective and user-friendly tools for preparing irrigation plans for individual crops; the software is able to prepare a more tailor-made plan. In practice, such plans can be supplemented with the use of soil water sensors, such as tensiometers, to assist in determining irrigation frequencies and to adjust volumes. This combined approach (an irrigation plan based on estimated ET_c together with sensors) is an effective way to ensure optimal irrigation of greenhouse-grown crops.

Irrigation scheduling with sensors

The use of sensors to monitor soil or plant water status offers the potential to irrigate in accordance with the characteristics of individual greenhouses and cropping conditions (e.g. variations in greenhouse characteristics, crop management and cycles, and soil characteristics). Additionally, these sensors offer the potential for a fine degree of crop management, such as applying controlled stresses for product quality considerations, and control of drainage for salinity or environmental management. Soil water and plant water status sensors can be used on their own as “stand-alone” methods; the two approaches can be combined; they can be used with the FAO method for estimating crop water requirements (Allen *et al.*, 1998); and they can be used as a supplement to irrigation management based on experience.

Until the late 1980s, there were few sensors available for measuring soil and plant water status; most required manual measurement, and their use in commercial farms was very limited. Recent technological developments have enabled the development of a new generation of sensors employing recent advances in electronics and information technology. Information on soil and plant water status can now be sent directly to a personal computer, mobile phone or used to automatically activate irrigation controllers. In Mediterranean greenhouses, intensive crop management and small greenhouse size are factors that favour the use of such monitoring technologies.

Irrigation scheduling with soil water sensors

Soil water sensors measure:

- volumetric water content of soil (Θ_v)
- soil matric potential (Ψ_m)

The Θ_v is the ratio of soil volume occupied by water. The Ψ_m measures the force of retention of soil water by the soil matrix (particles), and indicates the availability of soil water for crops. Whereas interpretation of Ψ_m data for irrigation management is straightforward, interpretation of Θ_v for practical irrigation management requires protocols or site-specific experience (Thompson and Gallardo, 2003). Soil water sensors can be read manually or with continuous automatic data collection; continuous recording allows more detailed information of the dynamics of water use by the crop and its movement in soil.

Soil water sensors can be used with different configurations depending on crop type, irrigation system, cost and mounting of sensors on probes (Thompson and Gallardo, 2003). One sensor should be placed in the zone of maximum root concentration; additional sensors can be placed at different depths (e.g. below the roots to control drainage, to the side of the plants to control the size of wetting bulbs from drip irrigation). The most commonly used sensor configurations are:

- one sensor within the zone of major root concentration
- one sensor within the zone of major root concentration complemented by one or more deeper sensors

Irrigation management with soil water sensors is based on maintaining soil water between two limits (Thompson and Gallardo, 2003):

- lower limit (drier value) – indication of when to start watering
- upper limit (wetter value) – indication of when to stop watering

The difference between the two limits is an indication of the volume of irrigation required. The lower limit most commonly chosen permits depletion of soil water without stressing the plant; it can also be used to impose controlled deficit irrigation. The upper limit is normally chosen to prevent excessive drainage from the root zone. It can also be reduced when controlled deficit irrigation is required. The simplest way to determine the volumes to be applied using soil water sensors is to use the selected lower and upper limits to evaluate irrigation (based either on experience or on the use of the FAO method) and then to adjust the applied volumes so that irrigation is maintained within the two limits. Thompson and Gallardo (2003) presented a comprehensive review on the use of soil water sensors for irrigation scheduling in greenhouses.

Soil water sensors can be used either manually or automatically to assist with irrigation management. Manual use involves manual programming of irrigation (volume, frequency) following revision of soil water data. Automatic use involves

either automatic initiation of irrigation for a fixed period, or both automatic initiation and cessation of irrigation. Automatic control of irrigation requires automatic data recording with short measurement intervals and sensors with rapid responses to changes in soil water status, and a suitable interface with an irrigation controller. Soil water sensors are a dynamic and constantly changing area of technology for technical and commercial reasons. Information on available sensors and their use for irrigation scheduling is provided by Thompson and Gallardo (2003) and Charlesworth (2005).

Soil matric potential sensors

In non-saline conditions, soil matric potential (Ψ_m) is a good approximation of the total soil water potential (Ψ_s). In saline conditions, osmotic potential may contribute significantly to Ψ_s . The Ψ_m generally provides a useful measure of the availability of soil water to plants. When using Ψ_m , the contribution of salinity to Ψ_s should be considered separately. Some authors (e.g. Hansen *et al.*, 2000) and equipment manufacturers have indicated the upper and lower limits between which the Ψ_m should be maintained in the root zone for horticultural production in soil. These limits depend on crop species, crop developmental stage, soil texture, and the evaporative conditions. Generally, higher (i.e. less negative) values are used for limits in lighter textured soils. As a general guideline for greenhouse-grown vegetable crops with high frequency irrigation, Ψ_m intervals of -10--20 kPa, -10--30 kPa and -20--40 kPa for coarse, medium and fine textured soils respectively have been suggested (Thompson and Gallardo, 2003). Lower limits of -35--58 kPa were suggested by Thompson *et al.* (2007b) for different species of greenhouse-grown vegetable crops in a sandy-loam soil, based on initial detection of plant water stress.

The two types of matric potential sensors most suitable for protected horticultural crops are tensiometers and granular matrix sensors. Tensiometers are cheap, simple and easy to use. They require preparation and proper maintenance to provide accurate and reliable data (Thompson and Gallardo, 2003). There are three types:

- manual tensiometers – data are obtained from the visual reading of a vacuum gauge
- manual tensiometers – a switch directly activates the irrigation equipment when it reaches a predetermined value
- electric tensiometers – pressure transducers provide continuous measurement and can be used to directly activate irrigation

Most tensiometers usually have a working range of 0--80 kPa. This narrow range is often a limitation in open-field cropping systems. However, for greenhouse vegetable crops with high frequency irrigation, Ψ_m generally remains within these limits. Exceptions occur when the evaporative demand and leaf area are high (e.g.

with mature melon crops in May–June in SE Spain). Models of tensiometers are available from major manufacturers (Irrometer Co., CA, USA; Soilmoisture Equipment Co., CA, USA) that have a reduced operating range (e.g. 0–40 kPa); these models have a more rapid response and are suitable for coarse soils and some substrates where most plant available water is retained with less tension than in soil.

Granular matrix (GM) sensors measure the electrical resistance between two electrodes in a porous matrix (Thompson and Gallardo, 2003; Charlesworth, 2005). The most commonly used is the Watermark sensor (Irrometer Co., CA, USA). The electrical resistance between the two electrodes is a function of the soil matric potential. The water within the sensor matrix equilibrates with that of the soil. A hand-held reader is used to supply the current and read the values. Data can be recorded on data loggers or input to an irrigation controller. An internal factory calibration, in the hand-held reader, is used to relate measurement of electrical resistance to soil matric potential. For research applications, the user can provide other calibration equations (Thompson *et al.*, 2006).

GM sensors are cheap, simple, easy to install and have few preparation and maintenance requirements. The measuring range is -10–200 kPa. While they have a wider measurement range than tensiometers, they tend to be less reliable in wet soils (0–10 kPa) and have a slower response in soils that dry very quickly (Thompson *et al.*, 2006). In general, GM sensors are somewhat less accurate than tensiometers but require appreciably less attention. They have a life span of 5–7 years.

Soil volumetric water content sensors

Various groups of sensors measure the volumetric soil water content (Θ_v): neutron moisture-probe, di-electric sensors, and heat dissipation sensors. The di-electric sensors are those mostly used for irrigation scheduling (Thompson and Gallardo, 2003). There are three general types of di-electric sensor:

- TDR (time domain refractometer)
- TDT (time domain transmissometer)
- capacitance, or FDR (frequency domain refractometer)



Plate 5
Manual tensiometer installed in soil in a greenhouse

TDR sensors with stainless steel probes > 10 cm long are widely used in research; however, they are not widely used for irrigation management. TDT sensors are an adaptation of TDR sensors that are generally cheaper and electronically simpler, and consequently more suitable for use in commercial farming. Capacitance (or FDR) sensors are widely used in both research applications and to manage irrigation in commercial farms. Capacitance sensors are available in several different configurations, for example, probes of various lengths or rings at various depths (Thompson and Gallardo, 2003).

The capacitance sensor most used for irrigation management is the EnviroSCAN (Sentek Technologies, Australia) consisting of several ring-type sensors mounted vertically at various depths on a probe which is enclosed in a PVC tube within the soil. This equipment continuously registers soil humidity giving detailed information on the dynamics of soil water both within the root zone and below. These sensors can be used to automatically initiate and stop irrigation. The EnviroSCAN can be sensitive to changes in soil salinity (Thompson *et al.*, 2007c) which can affect its use where salinity is managed to increase fruit quality. Various models and configurations of the EnviroSCAN are available (Charlesworth, 2005).

When using Θ_v for IS, the determination of lower irrigation limits (i.e. when to irrigate) is not as straightforward as when using Ψ_m (Thompson and Gallardo, 2003). When using Ψ_m , standard commonly available values are used (e.g. Hansen *et al.*, 2000). With Θ_v , values have to be determined for each combination of crops and soil. Different protocols to determine lower limits for greenhouse vegetable crops in soil were evaluated by Thompson *et al.* (2007d).

Some models of di-electric sensor also measure soil electrical conductivity (EC); this is measured in the form of bulk soil EC which is the conductivity per unit volume of soil. Bulk soil EC is strongly influenced by soil water content and is more difficult to interpret than more commonly used measures of soil salinity such as saturated extract EC or soil solution (or pore water) EC. Some sensor



Plate 6

EnviroSCAN capacitance sensors for measuring volumetric soil water content: installation of an EnviroSCAN probe with four capacitance sensors at different depths (left) and an EnviroSCAN probe after installation (right)

systems use internal equations to calculate pore water EC values from bulk soil EC and Θ_v measurements.

Irrigation scheduling with plant sensors

Three kinds of plant sensors can be used for irrigation management (Gallardo and Thompson, 2003):

- stem diameter sensors
- sap flow sensors
- sensors of leaf/crop canopy temperature

Stem diameter sensors measure both stem contractions occurring during the day in response to transpiration and stem growth; both parameters are very sensitive to water stress. In recent years there has been considerable research with these sensors in woody crops, and some adoption in commercial farms. In vegetable crops, they are sensitive to water stress; however, in short-cycle crops, the rapid growth rate makes data interpretation more difficult (Gallardo *et al.*, 2006a, 2006b). Furthermore, their sensitivity to detecting water stress in greenhouse-grown vegetable crops decreases during winter conditions of low evaporative demand (Gallardo *et al.*, 2006a, 2006b).

Sap flow sensors that directly measure plant transpiration have similarly been mostly investigated in woody crops. Because of their high cost and technical complexity, they have been mostly used in research with limited use for irrigation management of horticultural crops.

The temperature difference between the leaf or the crop canopy and the environment is a sensitive indicator of plant water stress. Indicators proposed for irrigation based on this measure include the CWSI (crop water stress index). As yet, there have been few commercial applications of this method. However, research is continuing, particularly in combination with remote sensing technologies. To date, plant sensors have had less practical application for irrigation management than soil water sensors, particularly for vegetable crops.

General considerations regarding the use of sensors for irrigation

When sensors are used for irrigation management, there are two important practical considerations:

- replication, with a minimum of 2–3 sensors per crop
- location of the sensors, which should be representative of the crop

Other practical considerations include cost, ease of use, preparation and maintenance requirements, technical support, ease of data interpretation, availability of irrigation protocols, working language, and the user friendliness of software where computer use is required (Thompson and Gallardo, 2003).

In general, there is appreciably more use of soil sensors for irrigation management than of plant sensors. Of the soil sensors, probably the most used sensors for irrigation management are tensiometers and capacitance sensors. Two important considerations with capacitance sensors are the cost and sensitivity of some models to changes in salinity. Tensiometers are very suitable for greenhouse vegetable crops in soil because of their low cost, simplicity and reliability; they are not affected by salinity and their narrow working range is not usually a limitation in greenhouse soils that generally remain moist.

IRRIGATION SCHEDULING OF GREENHOUSE CROPS GROWN IN SUBSTRATE

Large areas of greenhouse crops are grown in substrate in the Mediterranean Basin, including approximately 5 000 ha in SE Spain. Substrate is mostly associated with newer greenhouses of relatively high technological level. These are nearly all free-draining or “open” substrate systems, mostly in perlite or rockwool, with some use of coconut fibre.

Due to the small volume occupied by the root system and retention of water by substrates at very low tensions, irrigation management of crops grown in substrate requires a much more precise control than for equivalent crops in soil. Additionally, the mineral substrates (e.g. rockwool, perlite) most commonly used for vegetable crop production have very little nutrient buffering capacity. In order to maintain plant available water and to prevent excessive fluctuations in root zone salinity, small frequent irrigations are applied. To prevent salt accumulation, leaching fractions of 20–40 percent are used; the leaching fraction increases with the salinity of applied nutrient solutions. A revision of irrigation scheduling in substrates in Mediterranean greenhouses is presented by Medrano *et al.* (2003).

The water applied in each irrigation must compensate for the crop water uptake between irrigations. The volume must take into account the water retention capacity of the substrate and the leaching requirements. As a starting point, the volume of irrigation can be calculated as 5–10 percent of available water in the substrate plus the leaching fraction. Irrigation frequency depends on climate and crop development stage. Most irrigation control methods used with substrate determine the frequency of irrigation and use fixed irrigation volumes.

The methods of IS in substrate are classified according to the information used to activate irrigation. Methods involve either direct activation, when irrigation is triggered with a sensor; or indirect activation, when a decision is made after processing previously collected climatic data. Sensors for direct activation may be soil water sensors or water level sensors. Where direct activation is used, the leaching fraction is commonly also measured, either manually or automatically, to ensure adequate control of substrate salinity.

The most commonly used method in commercial greenhouses in SE Spain is the use of water level sensors, also known as the demand tray system. These sensors are installed in a small water reservoir (commonly a tray) in which the volume of water (and therefore the surface level) is in equilibrium with the water content of the substrate. When the water level in the reservoir decreases, through crop uptake, to the physical level of the sensor, irrigation is activated. The physical height of the sensor is adjusted by the grower on the basis of measured drainage volumes and experience. This method can be used once the crop root system is established.

**Plate 7**

Irrigation of substrate-grown crops. Use of a simple bucket to collect drainage in order to measure and subsequently control the electrical conductivity (EC) of the drainage water

Of the soil water sensors, some di-electric sensors and tensiometers have been used for crop irrigation management in substrates (Thompson and Gallardo, 2003). The di-electric sensors include the EnviroSCAN, the Theta probe and WET sensor (Delta-T Devices, UK), the Decagon range of soil moisture sensors (Decagon Devices, USA), and the Grodan WCM Continuous Sensor (Grodan, the Netherlands). Tensiometers with a reduced scale (e.g. 0–40 kPa) and rapid response have been used with artificial substrates and culture media (e.g. sand). The most commonly used substrates in SE Spain – perlite and rockwool – retain water within a narrow range of Ψ_m values of 0–10 kPa; to irrigate these substrates using Ψ_m , specialized tensiometers are required.

**Plate 8**

Irrigation of substrate-grown crops: demand tray system located at the end of a tray containing sacks of substrate with a tomato crop (left) and close-up of the demand tray showing the screws controlling the height of two water level sensors (right)

The indirect methods of IS of substrate-grown crops are based on the estimation of crop water requirements from climatic data, in a similar way to the FAO method for soil-grown crops. The most common method used with substrate is to initiate irrigation on the basis of measurements of the integral of solar radiation above the crop. This method which is commonly used in Dutch greenhouses is discussed by Medrano *et al.* (2003). In this method, evapotranspiration is estimated from solar radiation using an empirical equation that includes a crop coefficient and a radiation transmission coefficient. In this method, an accumulated radiation threshold value is used to activate irrigation.

Transpiration models based on the energy balance have been developed for substrate-grown crops – an example is that of Baille *et al.* (1994), a simplification of the Penman-Monteith equation. These models are integrated into the irrigation programmer and irrigation is triggered when a specified volume of simulated transpiration has occurred. Practical application is limited by the requirements for climatic and leaf area data, and for data of physiological parameters such as stomatal and aerodynamic resistances. This method was adapted by Medrano *et al.* (2005) for cucumber in Almería and accurately estimated crop water uptake. The “Monades” software, based on transpiration estimation, was developed by Medrano *et al.* (2003) for automatic irrigation management of substrate-grown crops.

WATER-USE EFFICIENCY (WUE) OF GREENHOUSE CROPS IN MEDITERRANEAN CLIMATES

In greenhouse vegetable crops, the irrigation water-use efficiency (kg m^{-3} , WUE), expressed as the ratio between marketable crop production and total crop irrigation supply, is higher than in open field crops due to the low evaporative demand inside the greenhouse that reduces water requirements and the higher productivity of greenhouse-grown crops. The WUE of tomato crops grown under different growing conditions (open field, greenhouse, soil, substrate etc.) is presented in Table 6. In unheated plastic greenhouses in the Mediterranean Basin, WUE was similar between crops grown in soil or substrate, and increased under the following conditions:

- improved greenhouse structure
- increased length of growing season
- recirculation of nutrients in substrate-grown crops

The highest WUE values of 45 and 66 kg m^{-3} were for tomato grown in the Netherlands with glasshouses with heating and CO_2 enrichment (Stanghellini *et al.*, 2003; Table 6).

In the cropping system of greenhouses in Almería, WUE varied with crop species, with values ranging from 15 kg m^{-3} for autumn–winter-grown green

beans to 36 kg m^{-3} for spring-grown watermelon (Fernández *et al.*, 2007). The water productivity (WP, € m^{-3}), defined as the ratio of total value of production to total crop irrigation water supply, varied from 7.8 to 15.9 € m^{-3} and was highest for green bean crops (Fernández *et al.*, 2007). WP values of greenhouse crops are generally much higher than for open field crops throughout the world, including in Mediterranean areas, due to the low water use and particularly to the high economic value of vegetable crops grown out of season.

TABLE 6

Water-use efficiency (WUE) of tomato crops grown in different conditions and media

Cropping conditions	Country	WUE (kg m^{-3})
<i>Open field</i>		
Soil	Israel	17
Soil	France	14
Soil-processing tomato	Spain (Extremadura, Rioja)	7.4–8.5
<i>Unheated plastic greenhouse</i>		
Soil	Israel	33
Soil	France	24
Open substrate	Italy	23
Closed substrate	Italy	47
Soil enarenado- traditional greenhouse	Spain (Almería)	25
Soil enarenado- improved greenhouse	Spain (Almería)	35
Substrate-short season	Spain (Almería)	27
Substrate-long season	Spain (Almería)	35
<i>Glasshouse-climate controlled</i>		
Substrate-open system	Netherlands	45
Substrate-closed system	Netherlands	66

Stanghellini *et al.* (2003), Pardossi *et al.* (2004) and Gallardo *et al.* (2007)

GAP recommendations

Soil-grown crops

- For soil-grown crops in Mediterranean greenhouses, crop water requirements can be considered to be equal to ET_c because there is usually little depletion of soil moisture during a crop and no rainfall enters the greenhouse.
- Daily and seasonal ET_c of crops grown in Mediterranean greenhouses can be calculated using the FAO approach as the product of reference evapotranspiration (ET_o) and crop coefficient (K_c) values. ET_o can be calculated from climatic data using suitable adaptations of the Penman-Monteith equation or with relatively simple equations based on solar radiation data. For calculation of ET_o for subsequent estimation of ET_c , average values of long-term climatic data can be used because of the low interannual climatic variation associated with Mediterranean climatic conditions. Crop coefficients can be calculated using available models based on temperature inside the greenhouse. This enables adaptation to particular planting dates and lengths of growing cycles which vary appreciably depending on markets conditions. The standard values of K_c reported by FAO for outdoor vegetables are not suitable for the tall canopies of supported crops grown in greenhouses.
- There are simple tools (in Spanish) that are freely available (e.g. the PrHo software, look-up tables) to calculate ET_c for a given crop, greenhouse and season, using historical or real time climatic data. Furthermore, the software calculates daily gross water requirements considering salinity and irrigation uniformity. This material can be supplemented by soil water sensors (e.g. tensiometers) to ensure optimal irrigation of greenhouse-grown crops.
- Soil water sensors (alone or as a supplement of the ET_c method) are effective tools for optimizing irrigation of soil-grown crops. When using soil water sensors, growers and technical advisers should be aware of the limitations of the particular sensors being used, e.g. operational range, responsiveness and sensitivity to salinity. Manual tensiometers are effective soil water sensors with soil-grown crops grown with frequent drip irrigation. They are relatively cheap and simple to use; however, potential users should be aware that they require preparation and maintenance to be most effective.

Substrate-grown crops

- For substrate-grown crops in Mediterranean greenhouses, crop water requirements are equal to crop evapotranspiration (ET_c) plus a drainage fraction to prevent salt accumulation.
- A system of automatic irrigation scheduling is essential to manage the frequent small irrigations applied to substrate-grown crops. Frequent irrigation with small volumes is required because of the limited root volume and water-holding capacity of substrates. The available systems are methods based on:
 - sensors that trigger irrigation (e.g. water level sensors, soil water sensors suitable for substrates),
 - methods based on the estimation of crop water requirements from climatic data (e.g. radiation), or
 - transpiration models that can be integrated into the irrigation programmer.
- The control of root-zone salinity is a fundamental consideration for the irrigation management of substrate-grown crops.

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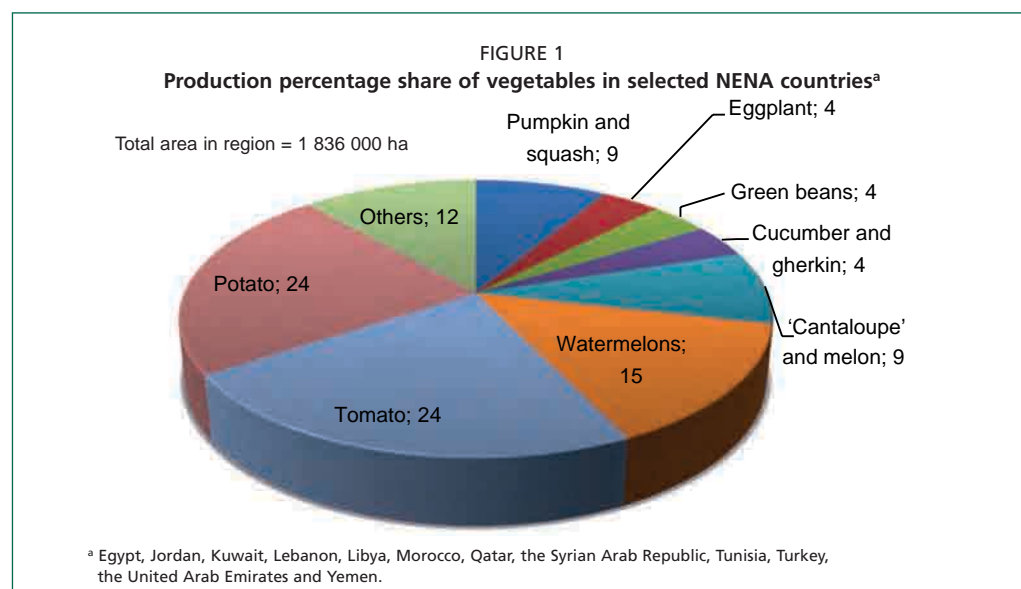
7. Protected cultivation for improving water-use efficiency of vegetable crops in the NENA region¹

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INTRODUCTION

In recent years, vegetables grown under protected cultivation in the NENA (Near East and North Africa) region underwent rapid expansion, with crops varying from one country to another. The total area of vegetable production in selected NENA countries exceeds 1.8 million ha (Figure 1) and includes: tomatoes (24%), potatoes (24%), watermelons (15%) and ‘Cantaloupe’ and melon (9%).



¹ Algeria, Djibouti, Egypt, Gaza Strip, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudia Arabia, Somalia, the Sudan, the Syrian Arab Republic, Tunisia, Turkey, the United Arab Emirates and Yemen.

The development of protected cultivation in Egypt is representative of the rapid revolution of this industry in the region as a whole. In 1985 there was a boom in the use of plasticulture in Egypt: the total area covered by mulching, low tunnels and plastic houses was about 1 658 ha in 1986 (360 ha for mulching, 1 000 ha for low tunnels and 298 ha for plastic houses). A year later, a ministerial decree established the National Committee for Protected Cultivation to be responsible for protected cultivation (research, development, training and extension) throughout the country. In 1990–91, the area was 12 363 ha, distributed as follows: 890 ha for mulching, 836 ha for plastic houses and 10 637 ha for low tunnels (Table 1).

Vegetable production under low tunnels has increased significantly in Egypt and is used mainly for early production of cucumber, tomatoes, ‘Cantaloupe’, sweet peppers, melons, strawberries and beans for local consumption and exportation. Low tunnels are simple to apply and manage; moreover they are cheaper than plastic houses.

Productivity of vegetable crops varies from one country to another, but in all cases tomatoes give the highest productivity (Figure 2). Protected cultivation is an important technology for improving vegetable productivity: it covers a wide time span of the year, and, most importantly, it saves water and boosts yields as a result of improved water-use efficiency ($WUE = \text{yield}/\text{water consumption}$).

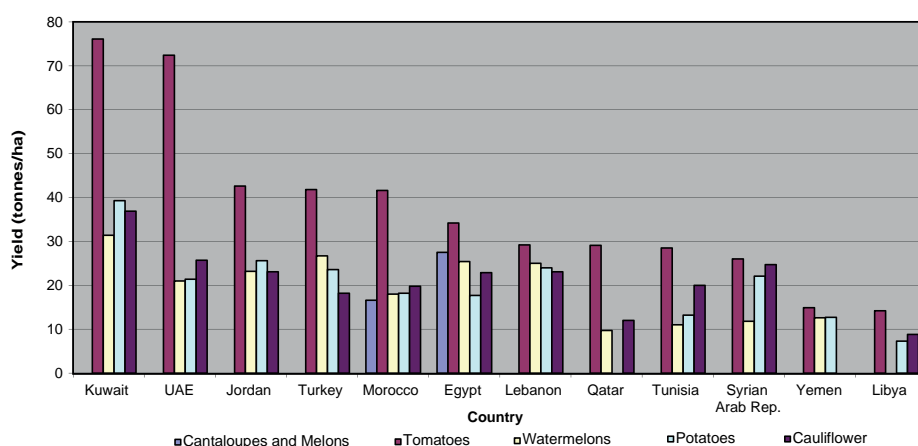
TABLE 1

Area of vegetable crops grown under different types of protection, 1977–2006^a

Period	Plastic houses (ha)	Low tunnels (ha)	Mulching (ha)	Total protected area (ha)
1977–1980	2	10	6	18
1985–1986	298	1 000	360	1 658
1990–1991	836	10 637	890	12 363
1995–1996	1 200	16 000	1 000	18 200
1996–1997	1 236	16 260	1 040	18 536
1997–1998	1 240	16 909	1 060	19 209
2000–2001	2 000	25 000	1 000	28 000
2005–2006	2 460	29 500	1 170	33 130
2007–2008	2 480	30 300	1 210	33 990

^a Egypt, Jordan, Kuwait, Lebanon, Libya, Morocco, Qatar, the Syrian Arab Republic, Tunisia, Turkey, the United Arab Emirates and Yemen.

FIGURE 2
Productivity of some vegetable crops in some NENA countries



WATER RESOURCES IN THE REGION

Water resource management and water availability are among the most important political, social and economic issues of the twenty-first century (Harsh *et al.*, 1989; Krug, 1989; Medany *et al.*, 1997). In Egypt, the misuse of limited water resources causes serious yield reductions in traditional agromanagement systems. Protected cultivation can easily double the water-use efficiency of vegetable crops as crop water requirements are easily managed under protected cultivation systems.

Irrigated areas and irrigation techniques

Almost 40 percent of food production in the Mediterranean is derived from irrigated farming systems where irrigation accounts for almost 72 percent of all freshwater withdrawals across the region (UNESCO, 2006). In the last two decades, due to the increasing waves of drought in south Mediterranean countries, supplemental irrigation areas have gradually increased to cover more than 50 percent of the rainfed agricultural area.

As the proportion of irrigated area in the total cultivated area increases, agricultural productivity becomes more stable and the effects of climate variability under current conditions are felt less. On the other hand, as a result of global change, the water demand of irrigated agriculture rises due to higher evapotranspiration and increased competition between key water sectors. Egypt has the highest proportion of irrigated area among the Mediterranean countries with over 95% of Egyptian cultivated area dependent on irrigation. Albania has the second highest irrigated area percentage (49%), while for other Mediterranean countries the irrigated area accounts for less than 40%.

Concepts of water-use efficiency

Irrigation efficiency

The original concept of water-use efficiency began with the term “irrigation efficiency” defined by Doneen and Westcot (1988) as the application of the least amount of water required to bring the root zone up to field capacity. If the amount of water applied grossly exceeds that actually needed for replenishment, the irrigation efficiency is very low. Irrigation efficiency or water application efficiency is calculated using the formula:

$$Ea = Et/Id$$

where:

Ea is application efficiency

Et is evapotranspiration (potential Et or Et0)

Id is irrigation water delivered at the farmgate

Irrigation application efficiency (Ea) is the ratio in % of water delivered at the farmgate to the amount stored in the active root zone. This ratio can vary from extremely low values to values approaching 100 percent (Israelsen and Hansen, 1962). However, in normal irrigation practices, the application efficiency of surface irrigation is about 60%, of well-designed sprinkler irrigation systems 75% and of drip irrigation up to 90%.

Water-use efficiency

Water resource problems often derive from lack of efficiency in water use in agricultural, industrial and domestic supply. Hamdy and Lacirignola (1999) reported that agriculture is by far the most important water-use activity; it is probably also the sector least efficient in water use. Low irrigation efficiency can be primarily attributed to water mismanagement, in addition to technical problems of conveyance, distribution or on-farm application, as well as poor maintenance of irrigation structures, often resulting from inadequate investment in operation and maintenance. In order to increase irrigation efficiency, it is necessary to improve system water management and on-farm water management; for the latter, the farmer's role is crucial.

Irrigation efficiency was developed to optimize land- and water-use requirements, especially for agronomic purposes. Tanner and Sinclair (1983) presented a detailed and comprehensive review of the different methods and models of calculating water-use efficiency. The phrases “efficient water use” or “water-use efficiency” are intrinsically ambiguous in relation to crop production: they could mean saving water from a given supply for crop use, or increasing production per hectare per unit of water evaporated from the soil or transpired from the plants in the field.

The term water-use efficiency has been employed very loosely by plant scientists and agronomists to refer to a range of observations, from gas exchange

by individual leaves for just a few minutes to grain yield response to irrigation treatments over an entire season (Sinclair, 1984).

For agronomists, water-use efficiency (WUE), measured in kg/m³, is commonly defined as:

$$WUE = \frac{\text{yield per unit area}}{\text{water volume used to produce yield}}$$

The quantity of water used to produce yield may be expressed in different ways. The simplified way of calculating water-use efficiency is:

$$WUE = (N/T)/(1 + (E/T))$$

where:

E is evaporation

N/T is transpiration efficiency²

N is dry matter production

T is transpiration (Gregory, 1991)

Tanner and Sinclair (1993) analysed crop water-use efficiency results and reached the conclusion that further substantial improvements could be achieved through plant breeding as well as appropriate agronomic practices. However, in a broader geographical sense, substantial improvements in water-use efficiency can be made by matching crop production with areas of low vapour pressure deficit. In general, solar radiation, saturation deficits and evapotranspirational demand in a region increase as precipitation and cloudiness decrease. Climatic divisions for regional aridity in the contiguous United States were reported in areas where saturation deficits and evapotranspiration increase. Although potential productivity under irrigation can increase with aridity because of increased sunshine and extended growing period, advection adds to the evapotranspiration of irrigated fields with no concomitant increase in productivity.

Irrigation in humid areas

Since irrigation often produces yield increases in humid regions (where precipitation exceeds 750 mm per day), Tanner and Sinclair (1983) conclude that overall crop water-use efficiency in the United States can be best improved by placing greater emphasis on water management and irrigation technology in humid areas. In addition, increased yields could be achieved in humid regions with a much lower water input than in more arid areas: rainfall provides much of the required water, and transpiration losses are lower. An increasingly important consideration is that in humid regions – where there is a much greater water availability, usually of high quality – salinization is not a problem. Further considerations are detailed below.

² The amount of dry matter in grams produced by an amount of water transpired in litres.

- Irrigation research has been neglected in humid regions, where unpredictable rainfall poses different technical problems to those in dry regions where most irrigation technology has been developed.
- The soil fertilizing practices adopted in humid regions have been developed with little regard for the interaction between water-use efficiency and irrigation efficiency; research is required to develop sound fertilizer and irrigation practices that recognize this interaction and minimize leaching while maintaining an adequate soil water supply for the crop – increasingly important with shallow-rooted crops and sandy soils. Irrigation practices that do not bring the root zone to full water supply are essential for reducing energy use in irrigation and avoiding nitrate contamination of the groundwater (Tanner and Sinclair, 1983).
- Erosion hazards are greater in humid regions where unpredicted precipitation can follow irrigation; on sloping land, irrigation practices must be integrated with sound conservation measures.
- Plant disease, insects and weeds not found in dry regions can be a problem under irrigation in humid regions.
- Trafficability for field operations is often a problem on fine-textured soils under natural rainfall, and the problem worsens when crops are irrigated.
- Increasing energy costs affect the feasibility of irrigation in both arid and humid regions; further assessment is required in humid regions where the availability of the water supply and probability of yield increases are important factors. Indeed, the use of electric power for pumping is seasonal, and there are weather-induced uncertainties about timing irrigation; therefore management of power generation and distribution for load peaks is an increasing problem.

In short, scheduling irrigation must help optimize fertilizer use, soil conservation, pest control, power requirement, electric load management, and other crop management practices for high productivity and minimal environmental damage (groundwater pollution, soil loss) in the presence of unpredictable rainfall. Improved medium-scale forecasting of rainfall would help improve water-use efficiency, but given the forecasting advances already made since 1900, there is little room left for further improvement.

Factors affecting water-use efficiency

- **Water delivery systems.** Open canals, lined ditches and pipelines vary in their ability to convey water and in the losses made. At macro level, the water conveyance system is a major factor in determining water-use efficiency.
- **Irrigation systems and water delivery systems.** There are various methods for increasing water availability for transpiration. Factors to be considered for maximizing the availability of water are improvement of water movement in the soils, absorption by the roots and movement through the plant.

- **Crop shape and morphology.** When soil evaporation is low, crops with closed-leaf canopies (depending mainly on genetic factors) have better water-use efficiency.
- **Climatic factors.** The climate affects the physical processes controlling crop evapotranspiration and is key to the management and minimization of water loss. Water deficits developing in crops severely limit the ability of crops to produce an economic yield.
- **Management.** Appropriate decisions aim to increase the amount of water available for crop production and to improve crop growth characteristics in order to increase economic yield.
- **Economic considerations.** The cash return per unit of yield is central to improving efficiency.
- **Techniques for predicting yield.** The economic component of the crop must be considered. Crop productivity per unit area of land and water consumption per unit of yield must be taken into account. Maximum cash return per unit volume of water in a given area is important in crop selection.
- **Social and political factors.** They condition whether or not to give priority to increasing water-use efficiency in crop production in a given area.

Efficient water management systems

Information related to on-farm water use is available in a wide range of publications. This section explores the methods and approaches to improving water-use efficiency in agriculture. Water-use efficiency varies depending on the irrigation system. It was reported by Doneen and Westcot (1988) that the amount of water required for irrigation can be estimated by sampling the soil at several places in the field and estimating the moisture deficit. The water application is then calculated allowing for the possible losses. Irrigation efficiency for sprinkler irrigation is 60–70%, localized irrigation approximately 80%, basin irrigation 45–75%, and furrow irrigation 40–65%.

Irrigation timing during the hot dry season can be estimated on the basis of the consumptive use. If the maximum consumptive use rates are known for the crop and area, divide the available moisture held in the rooting depth of the soil (mm) by the consumptive use rate (mm/day) to estimate the number of days between irrigations. This procedure should not be used for early season irrigations; neither does it apply to young plants with incomplete root development, or to special applications, such as preplanting or leaching irrigations. For all irrigation methods, it may be assumed that a uniform soil will absorb about the same amount of water in one location in a field as in another, if the water is in contact with the soil for the same length of time, i.e., if intake “opportunity time” is the same at all points in the field, uniform application of water can be expected throughout the field. While most irrigation methods do not permit water to be applied for exactly the same length of time in each place, they can share this goal.

Improving irrigation efficiency – GAP recommendations

Before irrigating, check the soil moisture in the root zone at several locations. Estimate the amount of water needed to bring the soil to field capacity. About 2–3 days after irrigation, check the soil moisture again. The moisture should be close to field capacity throughout the rooting depth. There should be no dry spots or dry layers in the field.

Determine the depth of water in centimetres applied to the field during irrigation. This will require the measurement of the stream size and the period of time the water was delivered to the field. Then calculate the depth applied. For sprinklers, multiply the application rate in millimetres by the number of hours that the sprinklers operate at one setting.

How does the estimation of the amount of water needed compare with the amount delivered to the field? Approximately what irrigation efficiency was obtained? High efficiency can be secured. However, if only a small amount of water is put on dry soil, irrigation may be poor.

During an irrigation, check whether the intake opportunity time is about the same throughout the field. When irrigating using the border method, does the water stand about as long at the lower end and middle of the field as it does at the upper end? If furrows are used, does the water reach the lower end in about one-fourth of the total time that it is at the upper end? Are basins and level borders filled quickly?

Observe the amount of irrigation water running off the surface of the field as waste. A large amount of surface runoff from a border indicates that the stream is too large or that water has been run into the border strip for too long. When the water in a well-designed border (not a level border) approaches the lower end of the strip, the stream may be reduced or cut off at the upper end. In this way, even distribution is obtained with little or no runoff. The stream size must be properly adjusted to the soil intake rate and to the border length if the border is to be evenly irrigated without excessive runoff. If furrow runoff is excessive, the furrow stream should be reduced to about one- or two-thirds of the initial flow after the water reaches the lower end.

Watch for evidence of too much water being used as it may be as costly as using too little. Losses may occur in four different ways from overirrigation:

- high cost of excess water use
- leaching of plant food below the root zone of the crop plants
- waterlogging of some or all of the farmland
- reduced yield (of some crops)

Irrigation water should be used efficiently to achieve an even spread over the field and fill the soil reservoir. However, in the final analysis, it is the amount of crop produced with the water supply available that determines the real efficiency of the water use. Crops can be efficiently irrigated once or twice during the season and still fail to yield well because of lack of moisture during part of the growing season. Furthermore, water can only be used efficiently if good farming methods and good irrigation practices are followed.

The water supply rate applied through different irrigation systems should never exceed the rate of infiltration of the water in the soil, to avoid water runoff

PROTECTED CULTIVATIONS

The use of greenhouse and plastic house techniques has contributed significantly to the improvement of water-use efficiency. The plastic or glass cover creates a special microclimate (Abou Hadid and El-Beltagy, 1991) in which radiation and wind movement are lower but relative air humidity is higher than in the open field, favouring a reduction in evapotranspiration (Eissa *et al.*, 1991). Furthermore, the higher temperature results in increased plant growth rate and higher yield per unit area of cultivated land. Increase in yield and reduction in water consumption under protected cultivation was reported by Abou Hadid *et al.* (1992). Protected cultivation produces higher yields with less water: water-use efficiency is improved (Abou Hadid and El Beltagy, 1992). The efficient use of water in greenhouses is also reflected in the efficient use of fertilizers (Medany *et al.*, 1997). Many reports on this subject (Ismail *et al.*, 1996; El-Behairy *et al.*, 1996; Abd Elmoniem *et al.*, 1996) indicate that in plastic houses protected cultivation and soilless culture techniques improve the nutritional conditions and nutritional problems not easily solved under open field conditions.

SOILLESS CULTURE³

A remarkable example of the efficient use of water resources is the use of substrates in soilless culture for better vegetable quality and as a means for improving water-use efficiency.

To clarify the relationship between substrate culture and water-use efficiency, it should be noted that: field-grown tomato produces 3 kg/m³ of water; plastic house soil-grown tomato produces 17 kg/m³; tomato grown in substrate under plastic house conditions in Egypt was reported to produce 45 kg/m³.

Soilless culture techniques were developed under glasshouses in order to overcome major agricultural problems, including nutrition, plant diseases and environmental pollution. It was later discovered to be an efficient water-saving tool. The development of a simple low-cost hydroponic system was the main challenge to enable soilless culture. Several attempts to design and implement soilless culture techniques were made and proved to be economically viable and environmentally safe. Water-use efficiency was thus greatly improved and the chemicals used for nutrition and pest and disease control reduced to a very low level. Production costs are relatively high but future research looks to reducing costs and improving applicability on a large scale in arid lands.

Limited water resources and high population growth were the main factors leading to the use of intensive agriculture in Egypt. Protected cultivation was the first step, starting in the late 1970s and intensifying in the mid-1980s. Maximizing

³ Information on soilless culture is elaborated in chapter 12 and advantages of microirrigation systems are described in chapter 8.

crop yield per square metre of soil and cubic metre of water could be achieved through the use of hydroponic systems (Zayed *et al.* 1989).

A range of soilless culture options are available for use in Egypt. Nutrient film technique (NFT) and rockwool are the most widespread systems, despite the fact that rockwool needs replacing every other year, entailing an additional cost compared with NFT.

Efforts to introduce NFT in Egypt began in tourist villages where the soil could not be cultivated successfully. Water-use efficiency may also be improved by adopting other systems, such as aeroponic systems (El Shinawy *et al.*, 1996).

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8. Microirrigation

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METHODS AND SYSTEMS FOR MICROIRRIGATION

This section provides an overview of microirrigation systems used for greenhouse crops. It presents a description of the main components, the basic knowledge required for proper management and practical guidelines to deal with most common issues that farmers may need to address. The term “microirrigation” refers to those systems operating at low flow rates and low pressures ($< 1.5\text{--}2$ bar) and providing localized distribution of the water, normally in proximity of the plant or the root systems. The main components of microirrigation systems are:

- pump
- system of filters
- control valves
- delivery system:
 - mainlines, made of PVC or polyethylene (PE), to convey water from source to the submains
 - submains (PVC or PE) to supply water to the drip lines
 - drip lines, made mostly of LDPE (low density polyethylene), placed along the rows of the crop on which emitters are connected
 - emission devices through which water is delivered at the root zone of the plant via dripping, bubbling and microsprinkling (these can be of various types, suited to serve one or more plants)

Microirrigation systems have the following advantages:

- high level of irrigation efficiency (low risk of runoff)
- distribution of small volumes over long irrigation time
- possibility of irrigating during warmest hours
- reduced development of weeds
- reduced risk of pathogen attacks because of the low air humidity generated by these systems (moreover, the small wetted area from non-spray type microirrigation limits weed growth and, consequently, disease incidence)

- absence of soil compaction
- low operating pressures with consequent reduction of energy costs
- possible adoption of fertigation

The most frequent problem with these systems is the clogging of the nozzles. That is why it is essential to always include a filtering apparatus upstream of the distribution line.

Depending on the type of installation, the emitters are divided into two types:

- On-line drippers placed on the polyethylene line transporting water along the rows of the crop. They can be easily inserted on polyethylene pipes of different diameters allowing a good operational flexibility (number and spacing of the emitters can be adjusted to fit plant spacing for most row crops). Drip lines can be either suspended or laid on the soil surface.
- In-line drippers mounted along the pipe. They are an integral part of the polyethylene pipe. This type of dripper is more resistant to emitter occlusions; it is suitable for placing on the ground along the row of the crop or under the mulch.

Microirrigation systems can be grouped in six main categories:

- Systems with drip lines (operating pressure: 0.5–2.0 bar; flow rates 0.5–4 litres/hour).
- Systems with drippers (operating pressures: 1–4 bar; flow rates 2–20 litres/hour).
- Systems with emitters (operating pressures: 1–3 bar; flow rates 6–30 litres/hour).
- Systems with capillary tubes (operating pressures: 1–2.5 bar; flow rates 0.7–7 litres/hour).
- Systems with micro-/minisprinklers.
- Subsurface drip irrigation.

Systems with drip lines

This category includes the common perforated hoses, consisting of a thin tube of polyethylene (generally 0.15–0.20 mm) with holes at a fixed distance. The perforated tubes do not have a flow rate control system and, therefore, they do not guarantee uniformity of distribution, which tends to be quite uneven due to frequent clogging of the holes.

The true drip lines (where the waterflow is controlled) are divided into light drip lines and lines with dripper. Light drip lines, often used for annual crops planted in rows, are equipped with emitters that permit uniform water distribution thanks to a built-in labyrinth system that reduces both the pressure

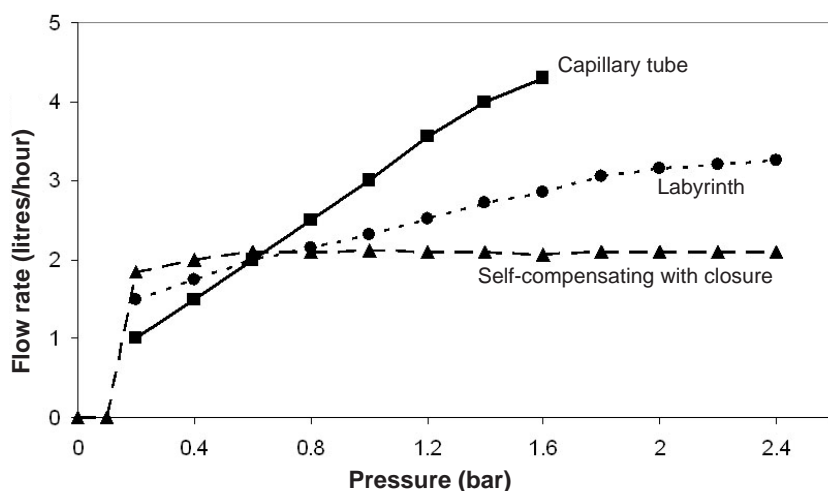
and the speed of the water. Drip lines with dripper, thanks to a greater thickness of the tube, last longer, provide more uniform irrigation and are suitable for long-term crops. There are also systems of drip lines with self-compensating drippers, which are used for sloping ground or for very long distances. In these cases, there will be marked differences between the pressure at the beginning and at the end of the drip line, affecting the flow rate of individual drippers. The self-compensating drippers maintain constant flow rates at different pressures and can efficiently work under these conditions. The self-compensating feature is given by a membrane of highly elastic plastic material that, solicited by water pressure, is deformed. The consequent expansion or reduction of the emitter's output section stabilizes the waterflow. Many self-compensating drippers also have a self-washing mechanism (anti-clogging) of the labyrinth. The working principle of the self-washing mechanism is that up to about 0.5–0.7 bar, the membrane does not deform causing a turbulent flow in the tube (greater than the nominal flow rate) capable of removing particles that may accumulate inside the dripper.

Systems with drippers

These systems consist of low density polyethylene tubes (diameter 16–25 mm) on which drippers are inserted at a proper distance based on the crop requirements. Button-type or arrow-type drippers may be used.

Button-type drippers comprise a special labyrinth (described above), allowing a certain uniformity of the flow. Also in this case, the self-compensating models provide a constant flow regardless of changes in the working pressure (Figure 1).

FIGURE 1
Variation of the flow rate of different types of drippers with the operating pressure



**Plate 1**

Tomato irrigated with arrow drippers inserted into the peat growing bags

These drippers can be mounted either directly on the line (delivering water to the plants via a thin tube of polyethylene) or at the end of short strands inserted on the main lines. Furthermore, there are special derivations that allow single emitters connected directly on the tube of polyethylene to have multiple outputs (up to eight), thus reducing the overall irrigation system costs.

A particular type of dripper is the anti-drain CNL (compensated no leakage). In this case, the dripper is equipped with a special membrane which completely closes the leakage of water when the pressure drops below a predetermined value (0.3–1 bar, depending on the model), preventing the emptying of the line. This may be an advantage for soilless crops, which typically require short and numerous irrigations. In this case, there is the risk of excessive supply of water in the final parts of the line for the emptying of the line itself.

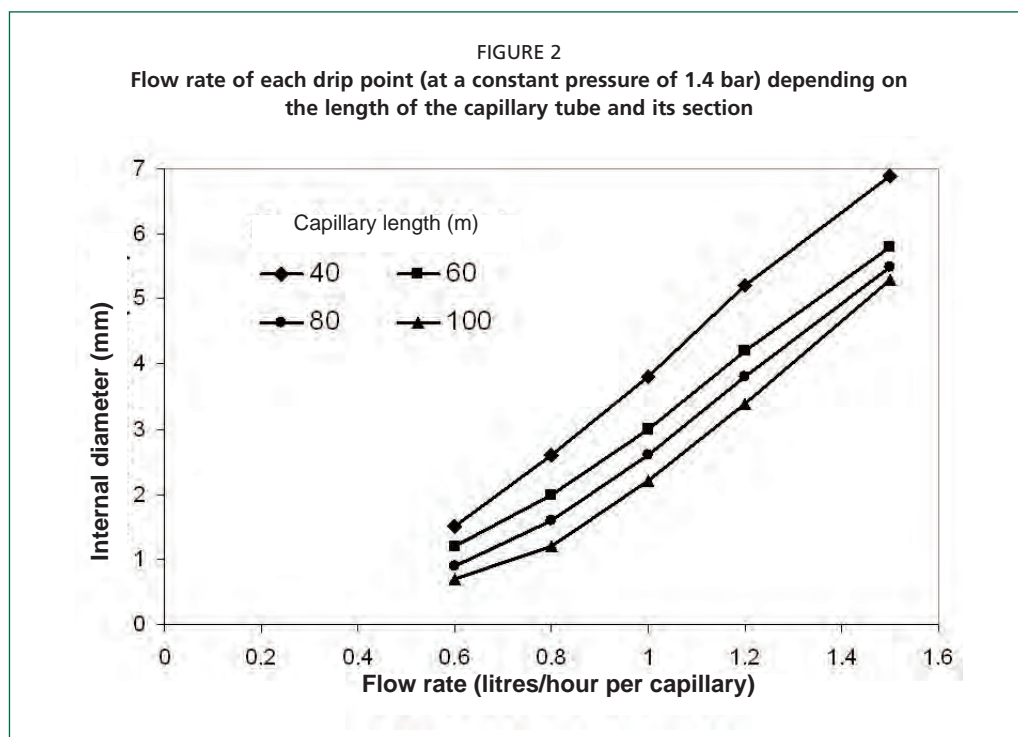
The arrow-type drippers are also labyrinth type but are connected to the main line via tiny tubes of polyethylene. These can be easily inspected for malfunctioning and cleaned by inverting the tiny tubes that connect the drippers to the main polyethylene lines.

Systems with intermittent emitters

These systems are characterized by high unitary flow rates (6–30 litres/hour, with operating pressures of 1–3 bar). The main advantages of these systems are the reduced incidence of clogging, as a consequence of the higher operating flow rate, and the greater wet surface compared with systems with classic drippers. These features overall allow more uniform growth of the root systems.

Systems with capillary tubes

These systems are becoming widespread due to their low cost and the possibility of having the lines already pre-assembled by the manufacturer, with considerable labour saving. This system consists of a polyethylene tube of 20–25 mm diameter, on which are inserted capillaries of 0.5–1.5 mm internal diameter with adequate length to reach the point of dispensing. In these cases, for a given pressure, the flow rate is directly proportional to the diameter of the capillary and inversely proportional to its length. Figure 2 shows the typical ranges in function of these two parameters.



The system is equipped with rods to be connected at the end of the capillary to allow proper positioning close to the plant roots. Although this type of system is economical, it does not provide uniform water distribution because of pressure losses along the line. Therefore lines with many drip points should be avoided. With this type, it is always advisable to use double-headed irrigation systems in a closed circuit so as to provide water under pressure to both ends of the main line with the capillaries. In this way the pressure gradient along the line is minimal.

Systems with micro-/minisprinklers

Microsprinkler systems have some of the advantages of both drip- and sprinkler-irrigation systems.

Sprinklers are conventionally classified as follows:

- microsprinklers (flow rate 30–150 litres/hour)
- minisprinklers (flow rate 150–350 litres/hour)

The sprinklers require operating pressures of approximately 1.5–2 bar and have emission holes calibrated between 0.8 and 2.3 mm. Therefore the flow rates are considerably higher than those used with the drippers and the infiltration rate (i.e. the rate at which the soil is able to absorb irrigation water) is slightly lower. Also the sprinklers can be standard-type or self-compensating, with the same features as described for the drippers.

These systems can be divided as follows:

- Dynamic, if they have parts that move during irrigation (also called microsprinklers or minisprinklers, depending on the flow rates) providing a circular wetting area with a greater radius than other systems.
- Static (no moving parts), also known as sprayers, able to provide wetting areas of different shapes (circular, semicircular, sectors).

The sprinklers can be mounted directly on the main lines or on branch lines, hanging from the tube itself or carried on rods inserted into the ground. Different combinations correspond to different irrigation needs or farm management, but may greatly influence the quality and the efficiency of irrigation. Sprinklers can be used to combine irrigation and protection from frost, provided that the irrigation system is automated. This practice is recommended in areas exposed to moderate, but dangerous spring frosts. Sprinklers that produce droplets with a large diameter are more efficient at transferring heat to the atmosphere and increasing the air temperature.

Subsurface drip irrigation

Subsurface drip irrigation refers to the use of drip hoses positioned underground at a certain depth. This system consents to directly wet the underground root zone and reduce the evaporative water loss at the soil surface (higher water-use efficiency). The main advantages of this system are as follows:

- System permanently placed at a depth > 15 cm and no labour required for disposal or replacement of the system.
- Reduced air humidity below the vegetation and consequent limited disease occurrence and weed development.
- Higher water irrigation efficiency (no losses due to evaporation and wind drift).
- Improved fertigation with nutrients distributed close to the root systems.
- Total practicability of the soil during irrigation.
- Possibility to use wastewater (no contact with soil surface or aerial part of the plants).

However, the technique is not fully implemented, as uncertainties regarding certain technical aspects remain:

- It cannot be used to promote germination or rooting.
- The costs are still high.
- Soil tillage needs to be more superficial.
- Powerful filtering is required because of very low flow rates at the drip points.
- Clogging of drippers or broken lines is not immediately visible.
- There is the possibility of intrusion of roots inside the emitter.

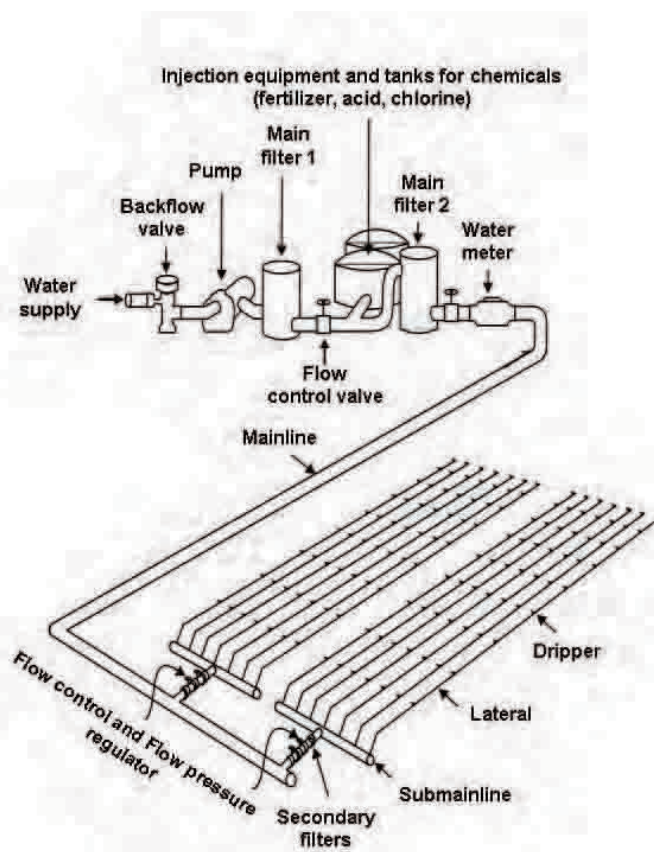
MICROIRRIGATION, WATER EFFICIENCY AND WATER SAVINGS

The performances of an irrigation method, or an irrigation system at field level or larger areas, are given by the ratio between the amount of water used by the crop and the volume of water distributed (given to the crop).

Irrigation efficiency

For an assessment of the irrigation efficiency, it is advisable to refer to the overall efficiency of irrigation (IE), i.e. the ratio between the volume of water held in the soil layer and usable by the crop and the water taken from the water source. Provided that a correct evaluation of the useful layer is defined, the overall efficiency is the result of different efficiencies that are encountered during the water transport from the source to the crop:

FIGURE 3
A schematic microirrigation system

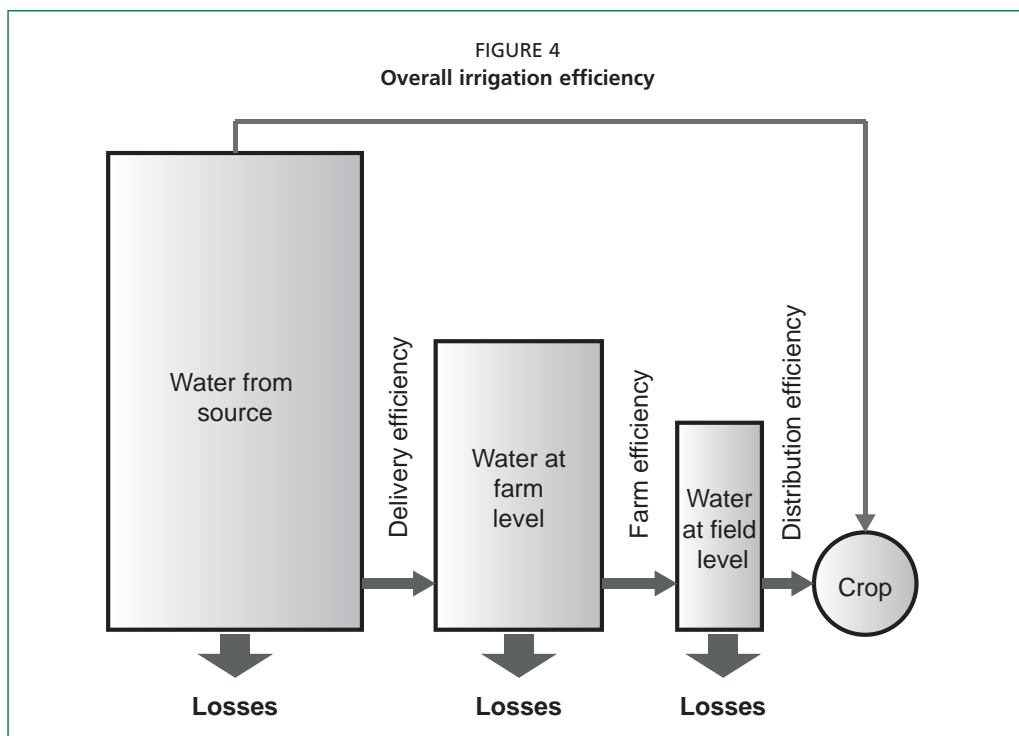


- DE (delivery efficiency) – the ratio between the volume of water delivered to the farm and the volume of water taken at the source (typically a river, lake or groundwater).
- FE (farm efficiency) – the ratio between the water volume that the farm distributes on irrigated land and the volume of water delivered to the farm or taken directly from a water source of the farm.
- WE (watering efficiency) – also known as distribution efficiency, it depends on the type and accuracy of the irrigation method used and expresses (in %) the ratio between the water volume retained in the soil layer and usable by plants and the watering volume; WE quantifies all the water losses that may occur during irrigation, resulting from the use of different irrigation methods and criteria for their use.

The overall irrigation efficiency IE is reached by combining the different efficiencies (Figure 4):

$$IE = DE \times FE \times WE$$

Compared with other common irrigation methods, such as surface irrigation and sprinkler irrigation, microirrigation is the most efficient. Surface irrigation is the most inefficient ($IE < 40\%$). With sprinkler and mechanized irrigation, the IE ranges from 60 to 85%. With microirrigation, IE can reach 90–95% in well-



designed systems, equipped with emitters of good constructive characteristics and used properly (i.e. with irrigation frequency and volume appropriate to both the crop and the soil). In principle, a good microirrigation system can enable the achievement of rational water use, high uniformity of distribution and high efficiency of application; it is also cost-effective. It requires: good system design, water application near the plants and high irrigation frequency, small volumes of watering distributed over long delivery times and low pressures. There follow examples of how water savings can be achieved by improving efficiency.

Case 1

Greenhouse farms not technically advanced, with (for various reasons) drip irrigation systems with relatively low efficiency (70%). Intervention to bring efficiency to 90% would result in the following savings:

For every 100 m³ of net irrigation requirements of the crop:
 with 70% efficiency, gross volume required = $100/0.7 \text{ m}^3 = 142.9 \text{ m}^3$
 with 90% efficiency, gross volume required = $100/0.9 \text{ m}^3 = 111.1 \text{ m}^3$
 saving = 31.7 m³ (i.e. 22.5%)

With the water saved it is possible to irrigate 28.6% of additional surface.

Irrigation requirements for a crop with net seasonal volume of 3 000 m³/ha:
 seasonal saving = $3\,000/0.7 - 3\,000/0.9 = 4\,285.7 - 3\,333.3 = 952.4 \text{ m}^3/\text{ha}$

Case 2

Technically advanced greenhouse farms using good drip irrigation systems (IE 85%). There is still margin for improvement.

For every 100 m³ of net irrigation requirements of the crop:
 with 85% efficiency, gross volume required = $100/0.85 \text{ m}^3 = 117.6 \text{ m}^3$
 with 90% efficiency, gross volume required = $100/0.9 \text{ m}^3 = 105.2 \text{ m}^3$
 saving = 12.4 m³ (i.e. 10.55%)

With the water saved it is possible to irrigate 11.8% of additional surface.

Irrigation requirements for a crop with net seasonal volume of 3 000 m³/ha:
 seasonal saving = $3\,000/0.85 - 3\,000/0.9 = 3\,529.4 - 3\,333.3 = 196.1 \text{ m}^3/\text{ha}$

Also in the second case, the potential benefit is appreciable. Improvement in efficiency can produce a substantial increase in the availability of water and this may be of fundamental relevance in situations of water scarcity.

With microirrigation, uneven distribution is often the main cause of inefficiency. The distribution uniformity (DU) is defined by the ratio (expressed as %) between

the average flow rate of one-quarter of drippers with the lower flow rates and the average flow rate of all the drippers.

DU:

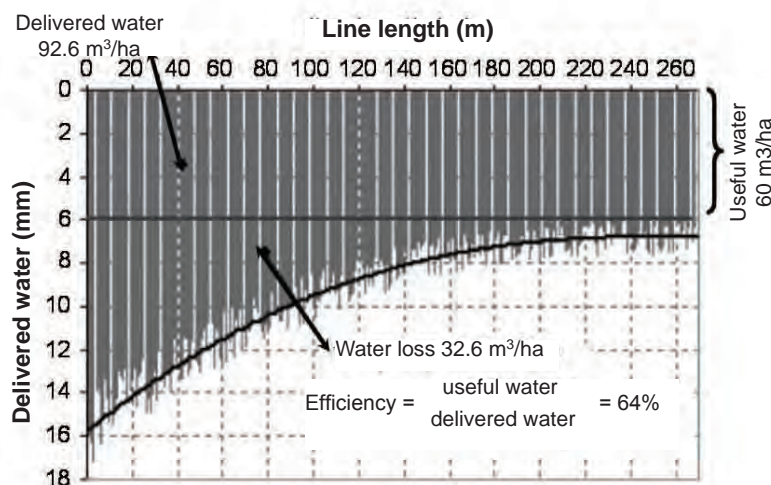
> 87%	excellent distribution uniformity
75–87%	good uniformity
62–75%	acceptable
< 62%	unacceptable

The consequence of non-uniform distribution of flow rates is explained in Figure 5, which shows the water penetration into the ground along a drip line. To provide sufficient water to the root zone of plants receiving lower flow rates, it is necessary to overirrigate the plants receiving normal flow rates. The excess water provided to the latter percolates below the root zone resulting in water waste and nutrient leaching. The ratio between the useful water to plants (net volume) and the water used (gross volume) indicates that the efficiency is only 64 percent in the example of Figure 5.

In the design phase of an irrigation system, DU can be estimated (in litres/h m) with the formula:

$$DU = 100(1 - 1.27CV)q_{min}/q_{mean}$$

FIGURE 5
Example of water loss relative to a watering of 60 m³/ha (6 mm)
due to low distribution uniformity



where:

CV is the average coefficient of technological variation of the delivery system

q_{\min} is the flow rate of minimum flow in litres/hour, calculated at the point of minimum pressure of the line

q_{mean} is the average flow rate of the line

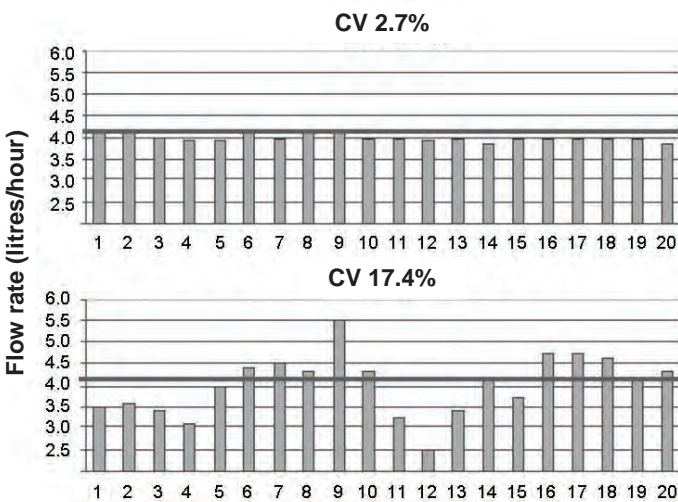
The smaller the difference in flow rate among emitters, the higher the DU (and thus quality for this specific parameter). The qualitative classification of the emitters is reported according to the CV identified experimentally. It is suggested to adopt dispensers with a CV below 5%.

CV for point source emitters:

- < 5% very good
- 5–10% good
- 10–15% poor
- > 15% unacceptable

An example of a coefficient of variation CV is shown in Figure 6, which describes the flow rates of two models of emitter, both with an average flow rate of 4 litres/hour, but with different technological uniformity. The first model has a CV of 2.7%, and is classified as “very good”, showing almost equivalent flow rates among emitters tested; the second has a CV of 17.4%, classified as unacceptable, with very different flow rates among emitters. In self-compensating

FIGURE 6
Differences of coefficient of uniformity (CV) in models of emitters with average flow rate of 4 litres/hour



emitters, in addition to the technological uniformity of flow rates and the CV, it is necessary to consider the “tolerance to variations in pressure”, i.e. the ability to effectively maintain unchanged flow rates at different pressure. The following is the classification of “tolerance to pressure variations” according to “x” in the relationship:

$$Q = k Hx$$

(pressure Q and flow rate H) of a self-compensating emitter. The higher the value of x, the lower the compensation of the model. A model with a value of x close to 0.5 is actually a frequently used emitter.

x for self-compensating emitters:

0–0.05	very good
0.05–0.10	good
0.10–0.15	moderate
> 0.15	poor

To obtain high DU and a real self-compensation, it is therefore necessary to use emitters characterized by a CV below 5% and $x < 0.05$.

How to maintain high efficiency

Although microirrigation, and in particular drip irrigation, have the potential for a very efficient, rational and economical use of irrigation water, it must be operated with caution. Frequent problems that may reduce the efficiency of the system arise from heterogeneity of flow between the emitters and excessive water localization and deep percolation.

Heterogeneity of flow between the emitters

The uniformity of water distribution in the field with drip irrigation may reach values well above 90 percent, especially with drip irrigation of crops at low plant density, where each plant is dependent on one or a few drippers. Poor uniformity of the flow rate between the drippers may:

- prevent precise measurement of the water distributed, forcing farmers to meet the needs of those plants receiving less water by overirrigating other plants (consequently water percolation and damage to the crop will occur);
- result in heterogeneous plant growth with competitive phenomena (implying higher harvest costs);
- prevent irrigation with specific water volumes estimated through the crop water balance; or
- make it impossible to carry out efficient fertigation.

Obtaining and maintaining high DU among the drippers requires the selection of emitters with high technological characteristics of uniformity of flow rate among the parts to be installed in the field and, in the case of self-compensating drippers, also good tolerance to pressure variations, conditions that must remain unchanged over time. Technical, agronomic and economic assumptions on which the realization of the microirrigation system is based may be jeopardized if these requirements are not met.

Uniformity of flow over time can also be achieved by avoiding obstructions or clogging of emitters by means of filtration and chemical treatment of the water. The presence of material in suspension or in solution in the irrigation water is a major cause of failure of irrigation, since this will clog the emitters. Factors that contribute to clogging of emitters are physical (suspended solids), chemical (precipitated salts) and biological (bacteria and algae). They may cause obstructions that must be carefully evaluated to determine whether it is possible or not to use a microirrigation system. In the presence of a high potential risk of obstruction, the water filtration becomes very complicated, expensive and often useless, and it may be advisable to switch to other irrigation methods. The filtration of irrigation water is always absolutely necessary to avoid partial or total obstructions of the emitters in the field, capable of compromising completely the uniformity of water distribution, with all the negative effects already described, including loss of efficiency and waste of water.

In this respect, the heart of the microirrigation system consists of the station of water filtration dimensioned according to the quality of available water and the sensitivity to clogging of the emitters. Usually, emitters with a lower flow rate have smaller passages and are therefore more sensitive to clogging. The efficiency of the filtering station is, therefore, crucial for the maintenance over time of the uniformity of water distribution. The following are the main types of filter:

- hydrocyclone filters
- sand filters
- screen (strainer) filters
- disc filters

The choice among different types depends mainly on the material in suspension in the water, which implies that coupling different types of filters may be required in some cases. For a correct choice of the type of filter, and relative filtration intensity, it is necessary to consider the diameter of both orifices and labyrinths of the emitters, the water quality and the flow rate to be filtered. The narrower the water passageways in microemitters, the finer the filtering material. Approximately the relationship between flow rate and passageway diameter is: 1 litre/hour,

0.7 mm; 2 litres/hour, 0.8 mm; 4 litres/hour, 1 mm; 8 litres/hour, 1.4 mm. In sand filters, disc filters and screen filters, the intensity of filtration is expressed as a function of the dimensions of the spaces left free for water passage. In general, filtering material with passages with a diameter below 1/7–1/10 the diameter of the orifice of the emitter is commonly used. Therefore particles passing through the filter will not block the emitter.

When the material in the irrigation water is in solution, filtering becomes ineffective. In these cases, the ordinary maintenance of the irrigation system must include chemical treatments inside the lines with chlorine or acid, able to avoid the clogging of the emitters.

Chlorination can be performed in one of the following modes:

- continuous – to prevent the growth of algae or bacteria or to precipitate the iron present in the water, with a concentration of 1–2 mg/litre;
- intermittent – to control excessive developments of micro-organisms or sludge, with concentrations of 10–20 mg/litre for about 1 hour;
- suppressing (superchlorination) – to dissolve concretions of organic material that clog the emitters, by injecting chlorine with concentrations up to 500 mg/litre.

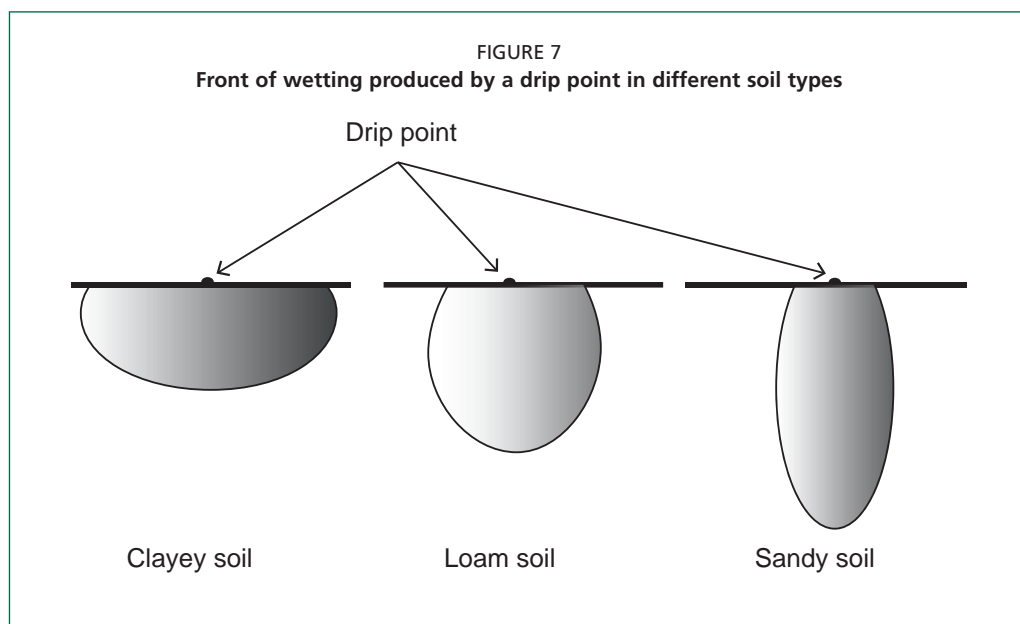
The injection of acid lowers the pH of the water in order to avoid precipitation of suspended solids such as carbonates and iron. The acid is also used, if necessary, to increase the effective antiseptic action of chlorine for the control of micro-organisms.

Water excess and deep percolation

While in sprinkler irrigation the entire soil surface is wet, the characteristic of microirrigation is to bring water in small volumes distributed at high frequency. Excessive localization can, however, result in reduced efficiency of microirrigation, for two main reasons:

- too low ratio between plant roots and volume of wet soil
- deep percolation for continuous supply of high water volumes (on a limited area of land)

The choice of an adequate number of emitters and their specific watering volume is not simple, but it should be made taking into account both the crop water requirements and the quantity of water storable in the useful layer of roots by different types of soil. The shape and the extension of wetted area below the drip points depends on the hydrological characteristics of the soil, the flow rate of the dripper and the water volume delivered (Figure 7). Regardless of the number of drippers, the soil volume moistened by each dripper is very limited on sandy soils and higher on clayey soils. In the latter situation, the volume of wet soil will be greater, with increased water contact with the root systems and less risk of deep



water loss (percolation). Too abundant and frequent volumes in the root zone, however, lead to saturation of the soil, nullifying the soil capacity to retain water and causing deep percolation.

In relation to the flow rate delivered by the drip point, the diameter of the wetted area (D , metres) increases with increasing values of the flow rate (F , litres/hour) according to the following relationships:

- sandy soil: $D = 0.12F + 0.31$
- loamy soil: $D = 0.11F + 0.68$
- clayey soil: $D = 0.10F + 1.19$

As the volume delivered increases, the water tends to deepen into the soil without substantially increasing the diameter of the wetted area. Particularly in very sandy soils, it is necessary to irrigate with a very high frequency, with a long duration of watering (so that plants may consume a significant fraction of the water supplied during the watering time) and to use a good number of drippers in order to fractionate the water volume in a greater soil volume. In these soils, a high number of emitters of low unitary flow rate is the best solution since it makes better use of the water storage capacity of the soil, supplies the water over a longer time and enables a greater volume of wet soil to come into contact with the roots. On sandy soils the frequency of irrigation may also be daily, returning to the crop the water evapotranspired the previous day. In the case of crops with high water consumption, subdividing the volume during the day is recommended.

AGRONOMIC TECHNIQUES, MANAGEMENT AND EFFICIENCY

Drip lines should be selected and dimensioned on the basis of operating pressures, which are critical to obtain the desired degree of uniformity. For this purpose, the assistance of specific computer programs for irrigation management and calculation of irrigation volumes may be useful. However, a properly designed system may not be sufficient to obtain high efficiency, if the correct techniques of irrigation management are not implemented.

When addressing problems relating to irrigation management, there are two areas requiring consideration: maintenance and agronomic aspects. With maintenance, it is sufficient to adopt rules of common sense, for example, flashing sufficient clear water in drip lines at the end of the fertigation, emptying drip lines regularly, taking prompt action to repair accidental breakage or slipping out of the pipes, maintaining the functionality of the filters.

With regard to the agronomic aspects, it is first necessary to consider the characteristics of drip irrigation that aim to provide water “continuously and constantly” (i.e. providing a gradual restitution of the water consumed by the crop, maintaining high levels of moisture in the wet zone of the soil where the roots are active). Limiting the oscillation of the soil water content between the field capacity and no less than 75 percent of the water usable by the plants would be to the benefit of the crop and improve the efficiency of the delivered water. Indeed, the gradual reintegration of water consumption involves frequent watering with low volumes which can be (almost) completely retained in the soil layer explored by the roots. Conversely, increasing the time intervals between the irrigations, involves the supply of higher volumes, part of which will go below the rootzone and therefore be wasted.

The choice of the correct water volume, in relation to the characteristics of the soil and the plant root systems, is therefore important for reducing water losses. The water volume must refer to the wet surface, taking into account the diameter of the area wetted by each drip point. As already mentioned in the previous paragraph, this depends not only on the soil type but also on the flow rate delivered by the drip point. On this basis, the following relationships show the approximate water volume (V, litres) retained in a soil layer of 40 cm, in three different types of soil, irrigating at 75 percent of the water usable by the crops (F = flow rate of drip points, litres/hour).

- sandy soil: $V = 1.50F + 0.53$
- loamy soil: $V = 3.93F + 7.62$
- clayey soil: $V = 5.71F + 27.69$

From these relationships it can be seen that, with drip points of a flow rate of 1 litre/hour, the retained soil water goes from a volume of about 2 litres on sandy soil to 33 litres on clayey soil, while on loamy soil the water volume retained in the first 40 cm is just above 11 litres.

It is evident that in a sandy soil, for example, with volumes greater than 2 litres per drip point, corresponding to operating times of over 2 hours, a part of the water percolates below a depth of 40 cm, where it cannot be easily used by plants. Therefore, in sandy soil it is absolutely necessary to irrigate frequently with low volumes. Even in clay soils, which could retain much higher water volumes in the same soil layer, it is advisable to irrigate with short time intervals, and consequently low volumes, to limit the phenomena of soil shrinkage, water loss and crop damage.

For good irrigation management, it is essential to know the crop water requirements in relation to the weather conditions and the phase of plant development, according to the methods and criteria reported herein.

GAP recommendations

- Microirrigation is the most efficient system for crop irrigation: cost/benefit analyses should nevertheless corroborate any technical choice.
- Clogging of the nozzles is a frequent problem in microirrigation: always include a filtering apparatus upstream of the distribution line.
- On sloping ground and over very long distances: use self-compensating drippers.
- Drip lines, systems with drippers, systems with intermittent emitters and systems with capillary tubes are all widely used, but have different costs and operating pressures: select appropriate system on a case-by-case basis.
- In areas exposed to moderate, but dangerous spring frosts: use sprinklers to combine irrigation and protection from frost, provided that the irrigation system is automated.
- Optimize overall efficiency of irrigation (IE) wherever possible, with attention to:
 - delivery efficiency (DE) – the ratio between the volume of water delivered to the farm and the volume of water taken at the source;
 - farm efficiency (FE) – the ratio between the water volume distributed by the farm on irrigated land and the volume of water delivered to the farm or taken directly from a water source on the farm;
 - watering efficiency (WE) or distribution efficiency which depends on the type and accuracy of the irrigation method used and expresses (in %) the ratio between the water volume retained in the soil layer and usable by plants and the watering volume.
- Improve efficiency of microirrigation systems: reduce the heterogeneity of flow between the emitters and avoid excessive water localization and deep percolation.
- For microirrigation management problems, take into consideration two main aspects:
 - Maintenance: Adopt rules of common sense, for example, flush sufficient clear water in drip lines following fertigation and empty them regularly, take prompt action to repair accidental breakage or slipping out of the pipes, and maintain filter functionality.
 - Agronomics: Drip irrigation aims to provide water “continuously and constantly” (i.e. gradual restitution of the water consumed by the crop, maintaining high levels of moisture in the wet zone of the soil where the roots are active). For optimal water management, it is recommended to limit the oscillation of the soil water content between the field capacity and not less than 75% of the water usable by the plants.

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9. Irrigation water quality for greenhouse horticulture

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INTRODUCTION

Water, in terms of both quantity and quality, is crucial to the success of horticulture greenhouse production. As water supplies are often limited, it is necessary to use low quality water for irrigation purposes. This is particularly true in Mediterranean countries, where growers increasingly face problems associated with low quality water. In this chapter the most important water physical and chemical quality parameters are discussed. These include pH, alkalinity and salinity. Furthermore, a review of the criteria for water quality assessment is presented. Water tests to be conducted prior to selecting a greenhouse site are also briefly described with reference to the official methods of water analysis. The presence of high soluble salts in irrigation water is one of the most limiting factors in greenhouse crop production. As an alternative to using seawater – a common practice in some Mediterranean areas (e.g. Almería, Spain) – wastewater from industrial processes or lower grade water from wells contaminated by seawater infiltrations can be used. Management and agronomic techniques that may be used to combat some of the problems associated with the use of these “waters” are discussed, including methods to correct poor quality irrigation water.

IRRIGATION WATER QUALITY PARAMETERS

The characteristics of irrigation water depend on the source. Irrigation water can be classified on the basis of its origin as:

- surface water (from rivers, canals, natural or artificial lakes);
- subterranean water (from springs, wells etc.);
- wastewater (from urban and industrial drains, subjected to various kinds of purification treatments).

For example, subterranean water in coastal zones may be of marginal quality for agricultural use owing to the high dissolved salt content, and municipal wastewater also, because of the associated health hazards.

The parameters characterizing irrigation water quality can be divided into three categories:

- **Physical:** temperature, suspended solids (soil particles, impurities etc.)
- **Chemical:** gaseous substances, pH, soluble salts, hardness, sodium and chloride concentration etc.
- **Biological:** algae, bacteria, various micro-organisms

Physical parameters

Temperature

For irrigation purposes, the water temperature must be as close as possible to that of the plants and the layer of substrate containing the root systems. Low temperature water contributes to modify the soil temperature (Wierenga *et al.*, 1971) which, in turn, reduces the root activity in terms of water and nutrient uptake from and to the roots (of carbohydrates and of growth metabolites, respectively). Low temperature water could also induce water stress by increasing the gap between plant transpiration and water uptake (Langridge, 1963). For horticultural crops, water can be considered cold when its temperature is less than three-quarters that of the air (Barbieri and De Pascale, 1991). In tomato, it has been proposed that reduced rates of mineral transport are responsible for slow growth at cool root temperature (Davies and Lingle, 1961).

Cold water can cause physiological disorders, especially in more delicate crops; water can be stored in basins to encourage the temperature to rise. Warm water can be used advantageously to warm crops as well as supply water needs; however, water at a temperature of over 35 °C is dangerous to plants. Water temperature can affect the end product: particularly in the cultivation of foliage plants, unsuitable temperatures can cause leaf spotting, which reduces product value.

Suspended solids

Solid substances of varying origin may be found in the water:

- Soil particles as a result of erosion.
- Very fine dispersion of clay, silicate and carbonate materials from the concrete, refractory, ceramic and glass industries.
- Different types of suspended matter disposed of in watercourses by various industries.
- Particulates contained in unpurified or partially purified municipal wastewater.

This type of pollution does not generally cause direct damage to the crops. Problems may arise when plants and commercial products are stained, leading to their depreciation in terms of health, hygiene and appearance – particularly important in the case of flower crops. However, solid substances suspended in irrigation water are more likely to damage the irrigation equipment. High solid matter content can lead to sedimentation of the suspended matter, blocking the equipment; this alters the waterflow, reducing the efficiency of the distribution networks and increasing the need for maintenance. There may be indirect damage to crops due to shortcomings caused by insufficient water availability and blockage of the distribution equipment, especially drip emitters. The problem of solid matter in irrigation water should be tackled in relation to the distribution method used. Microirrigation systems characterized by a high number of distribution points with small orifices and small-diameter tubes are more susceptible to blockages. The problem worsens when the water also contains agents causing blockages. An assessment of the blockage risk in relation to the presence of these substances is shown in Table 1.

Matter suspended in wastewater may include variable quantities of organic substances, leading to water distribution problems. Moreover, the use of wastewater containing suspended organic solids can lead to health and hygiene hazards. Pollution by natural organic substances is the most frequent form of surface water contamination and is due to urban drains, livestock farming and industry (for example, the food industry). The organic substances in the water begin to decay, leading to the increasingly fast breakdown of the original matter and the formation of very simple end compounds, such as carbon

TABLE 1
Influence of water quality on the potential for clogging problems in localized (drip) irrigation systems.

Potential problem	Units	Degree of restriction on use		
		None	Slight to moderate	Severe
<i>Physical:</i>				
Suspended solids	mg/litre	<50	50–100	>100
<i>Chemical:</i>				
pH		<7.0	7.0–8.0	>8.0
Dissolved solids	mg/litre	<500	500–2 000	>2 000
Manganese ^a	mg/litre	<0.1	0.1–1.5	>1.5
Iron ^b	mg/litre	<0.1	0.1–1.5	>1.5
Hydrogen sulphide	mg/litre	<0.5	0.5–2.0	>2.0
<i>Biological:</i>				
Bacterial populations	max. no./ml	<10 000	10 000–50 000	>50 000

^a While restrictions in use of localized (drip) irrigation systems may not occur at these manganese concentrations, plant toxicities may occur at lower concentrations.

^b Iron concentrations > 5.0 mg/litre may cause nutritional imbalances in certain crops.

dioxide, nitrates, sulphates and phosphates. Organic substances are primarily broken down by oxidizing bacteria. Their proliferation can lead to a dramatic reduction in the amount of oxygen dissolved in the water. The intensity of these processes is regulated by climatic and environmental conditions. Normally, high concentrations of natural organic substances in the water are accompanied by other pollutants, particularly pathogenic germs. Filtration is designed to eliminate suspended solid matter of mineral or organic origin.

In summary, suspended solids such as soil particles are potential problems since they can clog the irrigation nozzle and cause abrasion of irrigation equipment. Obstruction of emitters caused by the presence of solid particles in the water raises the cost and increases the maintenance of trickle irrigation systems, and can compromise their utilization.

Chemical parameters

Oxygen and other gaseous components

The presence of oxygen in the water is influenced by temperature and by the presence of biodegradable substances. However, its concentration is always restrained by the low solubility of air in water; for this reason, rainwater and surface water are to be preferred. CO₂, H₂S, SO₂ and CH₄ can also be found in their gaseous state and their presence can restrict water-use potential. The chlorine used to purify drinking water is sometimes present in gaseous form, but becomes volatile when in contact with the environment due to the combined action of light and air.

pH

The pH expresses the concentration of hydrogen ions (protons; H⁺) in an aqueous solution. More specifically, the term, which derives from the French *pouvoir hydrogène* (power of hydrogen), is defined as the cologarithm (to the base 10) of the concentration (in moles per litre) of H⁺ ions with the sign changed:

$$pH = -\log_{10}[H^+]$$

The pH can vary on a scale from 0 to 14 with a pH of 7 being neutral, less than 7 acid and above 7 basic or alkaline.

The pH regulates all biological functions and, if unsuitable, can inhibit certain vital processes. The pH of water, together with that of soil or the different cultivation substrates, influences the solubility of the various ionic species and, therefore, the nutrition provided by the medium. In fact, every nutritional element has a maximum solubility for clearly defined pH intervals. The optimum pH of irrigation water is commonly between 6.5 and 7.5; the minimum acceptable limit is 5.0. At lower pH levels, the presence of free acids can also cause direct damage to the root system of the crops. The reaction of the water can influence that of the substrate. Prolonged use of the same substrate causes the pH to move away from

The pH is an indicator of the acidity or basicity of a water, but is seldom a problem by itself. The main use of pH in a water analysis is for detecting an abnormal water. The normal pH range for irrigation water is from 6.5 to 8.4. An abnormal value is a warning that the water needs further evaluation. Irrigation water with a pH outside the normal range may cause a nutritional imbalance or may contain a toxic ion. Low salinity water (electrical conductivity of water, $EC_w < 0.2$ dS/m) sometimes has a pH outside the normal range since it has a very low buffering capacity. This should not cause undue alarm other than to alert the user to a possible imbalance of ions and the need to establish the reason for the adverse pH through full laboratory analysis. Such water normally causes few problems for soils or crops but is very corrosive and may rapidly corrode pipelines, sprinklers and control equipment.

Any change in the soil pH caused by the water will take place slowly since the soil is strongly buffered and resists change. An adverse pH may need to be corrected, if possible, by the introduction of an amendment into the water, but this will only be practical in a few instances. It may be easier to correct the soil pH problem that may develop rather than try to treat the water. Lime is commonly applied to the soil to correct a low pH and sulphur or other acid material may be used to correct a high pH. Gypsum has little or no effect in controlling an acid soil problem apart from supplying a nutritional source of calcium, but it is effective in reducing a high soil pH (pH greater than 8.5) caused by high exchangeable sodium.

The greatest direct hazard of an abnormal pH in water is the impact on irrigation equipment. Equipment will need to be chosen carefully for unusual water.

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optimum levels, generally in an upward direction; this phenomenon increases with the use of alkaline waters resulting from the presence of carbonates. If the pH difference is not excessive, the substrate can counter this type of change through buffer power. As with cation exchange capacity, the buffer power varies greatly according to the type of substrate and is extremely low in some inert substrates.

Water with a pH of 6.0–8.5 can be used for irrigation purposes. Decidedly acid (pH < 5) or basic (pH > 8.5) water is classified as anomalous for irrigation purposes. A reaction that differs significantly from neutrality always indicates an anomaly, such as the presence of certain salts.

Alkalinity

The term alkaline (pH > 7) is different from the term alkalinity (capacity to change or resist a change in pH). It is not uncommon to have irrigation water with a pH of 7.5 (alkaline), but with a low alkalinity value acceptable for growing plants. While pH is a measure of the hydrogen ion concentration, alkalinity is a relative measurement of water's capacity to resist a change in pH or its ability to change the pH of the growing media. Chemically, this is expressed in parts per million (ppm) of calcium carbonate equivalents ($CaCO_3$). Bicarbonates (HCO_3^-), carbonates (CO_3^{2-}) and hydroxyl ions (OH^-) are the primary chemicals contributing to the

TABLE 2

Recommended irrigation water alkalinity upper limits

Container	Alkalinity (meq/litre)	
	Minimum	Maximum
Plugs or seedlings	0.75	1.3
Small pots/shallow flats	0.75	1.7
4–5-inch pots/deep flats	0.75	2.1
6-inch pots/long-term crops	0.75	2.6

Will and Faust, 1999

alkalinity of water. Alkalinity increases as the amount of dissolved carbonates and bicarbonates rises. Irrigation water with high alkalinity (e.g. 400 ppm CaCO_3) will tend to raise the pH of the growing media over time and require more acid to lower the pH of the water to an acceptable level if desired (Table 2).

Water with a high alkalinity (e.g. > 100 ppm CaCO_3) requires a grower to consider using acid-type soluble fertilizers rather than calcium-based fertilizers. Acid injection is commonly used to manage water with high alkalinity.

Salinity (total soluble salts)

One of the most important characteristics of irrigation water is salinity. The salinity of water is simply direct evidence of dissociation of soluble mineral salts.¹

The higher a salt's concentration the more it contributes to salinity, particularly if dissociated. The most frequently found are nitrates, chlorides, sulphates, carbonates and bicarbonates of alkaline and alkaline earth elements (sodium, potassium, magnesium, calcium). Some individual elements (e.g. boron, chlorine, sodium) have equally important effects. When determining irrigation water suitability criteria, particular reference is made to:

- the total concentration of salts in the solution;
- the relative ratio of sodium (Na) to the other cations;
- the concentration of specific ions which may be toxic to plants (e.g. boron, chloride and sodium).

The use of unsuitable water (in terms of the quantity or quality of salts present) for irrigation purposes has a negative effect on the overall soil-water-plant relationship, sometimes even drastically restricting the normal physiological activity and productive capacity of the crops.

Salinity can be measured by means of analytical or electrical conductivity methods. In the case of analytical measurements, salinity is expressed as the

¹ Soluble salts may dissociate in water to form charged ions. If the ion carries a positive charge (+), it is called a cation. If it carries a negative charge (-), it is called an anion. The most common cations of interest in water are calcium (Ca^{2+}), magnesium (Mg^{2+}) and sodium (Na^+); the most common anions are bicarbonate (HCO_3^-), chloride (Cl^-) and sulphate (SO_4^{2-}). An electric conductivity meter simply measures the total relative amount of either the dissolved anions or the dissolved cations. Pure water, with few or no dissolved salts, is a poor conductor of electrons and the electrical conductivity value is very low or approaching zero. Interestingly, urea dissolved in water to make a fertilizer solution does not dissociate so it cannot be monitored adequately using an EC meter.

total content of salts dissolved in the unit of volume (g/litre or mg/litre) or as concentration of mineral salts in ppm. Water is defined as brackish when it has total salt content (fixed solids or total dissolved salts) of 2 g/litre (or 2 000 ppm) or more.²

Electrical conductivity methods take into account the osmotic pressure that a given saline concentration creates in the solution; the salinity index adopted in this case is electrical conductivity (EC): the unit of measurement was for many years the mho³ and, more specifically, the millimho per centimetre (mmho/cm) and micromho per centimetre (μ mho/cm) at 25 °C, where 1 mmho/cm = 1 000 μ mho/cm. The metric equivalent for mho is Siemens, or milliSiemens per centimetre (mS/cm) or microSiemens/cm (μ S/cm), where 1 mho/cm = 1 mS/cm = 1 000 μ S/cm. Scientific literature generally uses deciSiemens per metre (dS/m) to measure conductivity, with mS/cm and μ S/cm the established and accepted units of measurement for water salinity, where 1 dS/m = 1 mS/cm = 1 000 μ S/cm as measured by a conductivity meter. Water is defined as brackish when the EC is 3.0 dS/m or more (at 25 °C). It is possible to switch from one unit to the other by consulting specific tables or using formulae (Table 3).⁴

On the basis of electrical conductivity levels, water classification schemes have been proposed in order to identify classes of irrigation water (Table 4) and the salinity hazard of the irrigation water (Table 5).

Salinity hazard

Use of saline irrigation water can lead to three types of problem:

- increase in the osmotic potential of the circulating solution (osmotic effect) with increasing water absorption problems for the plants (physiological drought);
- effects of the chemistry and physics of the substrate;
- phytotoxicity.

² A more complete analytical index is provided by meq/litre. The meq/litre is calculated by dividing the ppm by the equivalent weight (EW) of the respective ion. The equivalent weight of one ion is calculated as the molecular weight divided by its valence. For example, with sodium, the EW is 23 (molecular weight of 23 divided by the valence, which is 1). If the concentration of sodium is 100 ppm, the concentration expressed in meq/litre is 4.3.

³ The basis for this unit came from the ohm, which is the unit used to measure electrical resistance. A 1-ohm resistance with 1 volt across it will conduct 1 ampere of electrical current. The electrical equation is:

$$V \text{ (volts)} = I \text{ (ampere)} \times R \text{ (resistance)}$$

where R is measured in ohms. The reciprocal of resistance is conductance, measured in mho (ohm spelt backwards).

⁴ The total salt content or total dissolved solids (TDS) is usually in ppm; it is calculated from the EC value (EC in mS/cm is multiplied by 640) to obtain total dissolved solids in ppm. For example, EC of 1.6 mS/cm (1.6×640) = 1 024 ppm. The meq/litre of total salts can also be estimated by multiplying the EC (mS/cm) by 10. For example, EC of 2.62 mS/cm $\times 10$ = 26.2 meq/litre.

TABLE 3

Conversion factors: commonly used units of measurement for parameters considered in irrigation water chemical analysis

Parameter	Unit of measurement	Conversions
Concentration of salts, ions and nutrients	1 ppm = 1 mg/l = 1 g/m ³	STD (g/l) = fixed solids (g/l) \approx 0.64 • EC (dS/m)
Electrical conductivity (EC)	μ S/cm; mS/cm; dS/m	1000 μ S/cm = 1 mS/cm = 1 dS/m
Calcium (Ca ²⁺)	ppm; mmol/l; mEq/l	mmol/l = ppm / 40; mEq/l = ppm/20
Magnesium (Mg ²⁺)	ppm; mmol/l; mEq/l	mmol/l = ppm/24.3; mEq/l = ppm/12.15
Sodium (Na ⁺)	ppm; mmol/l; mEq/l	mmol/l = mEq/l = ppm/23
Total hardness	ppm of CaCO ₃	ppm of CaCO ₃ = ppm Ca • 2.5 + ppm Mg • 4.1
	°F (French degrees): 1 °F = 10 mg/l of Ca + Mg (as CaCO ₃)	°F = ppm CaCO ₃ /10
	°dH (German degrees): 1 °dH = 10 mg/l of Ca + Mg (as CaO)	°dH = °F/1.79
Chlorides (Cl)	ppm; mmol/l; mEq/l	mmol/l = mEq/l = ppm/35.45
Bicarbonates (HCO ₃)	ppm; mmol/l; mEq/l	mmol/l = mEq/l = ppm/61
Sulphates (SO ₄ ²⁻ -S)	ppm of S; ppm SO ₄ ²⁻ ppm; mmol/l; mEq/l	ppm S = ppm of SO ₄ ²⁻ /3; mmol/l = ppm S / 32 mEq/l = ppm S/16
Nitric nitrogen (NO ₃ N)	ppm N; ppm NH ₄ ⁺ ; mmol/l; mEq/l	ppm of N = ppm of NO ₃ /4.43 mmol/l = mEq/l = ppm N/14
Ammoniacal nitrogen (NH ₄ ⁺ -N)	ppm N; ppm c; mmol/l; mEq/l	ppm N = ppm NH ₄ ⁺ /1.28 mmol/l = mEq/l = ppm N/14
Phosphates (PO ₄ ³⁻ -P)	ppm P; ppm P ₂ O ₅ ; ppm PO ₄ ³⁻ ; mmol/l	ppm P = ppm P ₂ O ₅ /2.29 ppm P = ppm PO ₄ ³⁻ /3.07
Potassium (K ⁺)	ppm K; ppm K ₂ O; mol/l; mEq/l	mmol/l = ppm P/30.97 ppm K = ppm K ₂ O/1.2 mmol/l = mEq/l = ppm K/39.1
Iron (Fe)	ppm; μ mol/l	μ mol/l = ppm/0.0558
Manganese (Mn ²⁺)	ppm; μ mol/l	μ mol/l = ppm/0.0549
Copper (Cu ²⁺)	ppm; μ mol/l	μ mol/l = ppm/0.0635
Zinc (Zn)	ppm; μ mol/l	μ mol/l = ppm/0.0654
Boron (B)	ppm; μ mol/l	μ mol/l = ppm/0.010
Molybdenum (Mo)	ppm; μ mol/l	μ mol/l = ppm/0.0959

μ S/cm: microSiemens per centimetre – mS/cm: milliSiemens per centimetre – dS/m: deciSiemens per metre – ppm: parts per million

mg/l: milligrams per litre – mmol/l: millimoles per litre – μ mol/l: micromoles per litre – mEq/l: microequivalents per litre

Pardossi et al., 2004

Saline stress physiology

The presence of salt in the circulating solution can inhibit growth for two reasons:

- Salt in the soil reduces the availability of water for uptake by plants, leading to reduced growth. This factor is called the “osmotic effect”.
- If an excessive quantity of salt enters the transpiratory flow of the plant, the cells will be damaged by the “phytotoxic effect”.

The osmotic effect reduces leaf development and growth of the root system, reducing stomatal conductance and, as a result, photosynthesis. The metabolic and

TABLE 4
Permissible limits for classes of irrigation water

Classes of water	Concentration, total dissolved solids	
	Electrical conductivity ($\mu\text{S}/\text{cm}$) ^a	Total soluble salts (ppm)
Class 1, Excellent	250	175
Class 2, Good	250–750	175–525
Class 3, Permissible ^b	750–2 000	525–1 400
Class 4, Doubtful ^c	2 000–3 000	1 400–2 100
Class 5, Unsuitable ^c	3 000	2 100

^a $\mu\text{S}/\text{cm}$ at 25 °C.

^b Leaching needed if used.

^c Good drainage needed and possibly harmful to sensitive plants.

Scofield, 1936

TABLE 5
Salinity hazard of irrigation water based on electrical conductivity (EC)

Hazard	EC (mS/cm)
Water for which no detrimental effects will usually be noticed. Little chance for increased salinity to develop.	<0.75
Water which may have detrimental effects on sensitive crops. ^a Moderate leaching required to reduce salt accumulations.	0.75–1.50
Water that may have adverse effects on many crops and require careful management practices. Salinity increases will result unless adequately leached.	1.50–3.0
Water that can be used only for salt-tolerant plants ^b on permeable soils with careful management practices and only occasionally for more sensitive crops. A high leaching requirement is necessary. Soil should be tested for salinity increases yearly.	3.0–7.5

^a E.g. field beans, lettuce, bell pepper, onion, carrot, string beans.

^b E.g. sugar beet, wheat, barley.

Hergert and Knudsen, 1977

cellular processes are similar to those relative to water stress. Normally salts are not absorbed by growing tissues at concentrations that can inhibit growth. In fact, meristematic tissue is largely supplied with nutrients through the phloem, from which salts are excluded. Furthermore, expanding cells can exclude incoming salts through the xylematic (sap) flow by means of vacuolar compartmentation. In this way, the salts reaching the plant do not directly inhibit the growth of new tissue. However, the presence of salts enhances leaf senescence. Continuous transport in fully transpiring leaves leads to a high buildup of ions such as Na^+ and Cl^- , with early tissue death. If new leaves manage to replace the old dead leaves, the photosynthetic process remains unaltered and the plant can produce normally. Otherwise, yield reduction will occur. Reduction in growth comprises two phases:

- When stress begins, the reduction appears as a consequence of the osmotic effect due to the presence of ions outside the roots.
- Subsequently, tissues are damaged and leaf senescence occurs; the rate at which old leaves die depends on the rate at which the ions are accumulated.

Irrigation water, particularly if the source is from groundwater, usually contains some amount of dissolved salts. Some of these dissolved salts (sodium, chloride, boron, fluoride and iron) are of greater concern to growers than others. Soluble solids are a concern since they are either directly toxic to the plants, impede the uptake of water by the roots or cause foliar spotting that lowers the overall value of the plants. Water high in soluble salts may be referred to as saline. Total soluble salts are easily measured by monitoring the electrical conductivity (EC) of the solution.

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Ion transport is controlled in four plant sites:

- the root cortex
- the xylematic tissue
- the point of contact between these two sites
- the leaves

Control in roots aims to reduce the quantity of ions transported to the upper part of the plant, whereas in the leaves salts are excluded in the phloematic sap. An additional mechanism takes place in numerous halophytes: they contain specialized cells (salt glands and bladders) for the elimination of excessive salts. Exclusion is particularly important for

perennials in which leaves can live for several years.

Assessing salinity tolerance

There is a linear relationship between the salinity of the soil and plant production, expressed as follows (Mass and Hoffman model, Maas and Hoffman, 1977):

$$P = 100 - b(EC - a), \text{ with } EC > a$$

where:

P is the crop production compared with the maximum possible production in optimal conditions (%)

EC is the mean electrical conductivity of a saturated paste taken from the rootzone (in mS/cm or in dS/m)

a is the salinity threshold expressed in mS/cm (or in dS/m)

b is the slope expressed in percent per mS/cm (or in dS/m)

Obviously, some species are more tolerant to salt than others. Tolerance is usually linked to the percentage of biomass produced in saline soil compared with non-saline soil, after permitting growth for an extended period of time. For ornamental species, quantity of flowers and presence of aesthetically perfect leaves are also considerations. Various studies have attempted to classify the degree of tolerance⁵ of cultivated species to salinity. Table 6 shows the degree of tolerance to salinity in different vegetable crops.

⁵ The effects of salinity on plant production quality are almost always negative at high stress levels, but in conditions of moderate stress, the positive effects can significantly outweigh the negative effects. For example tomatoes have a better colour and increased total soluble solids, while melons display improved organoleptic characteristics.

While much progress has been made in the classification of the various plant species on the basis of their level of tolerance to salinity, the latter is highly variable depending on genotype, soil and climate conditions and the agronomic techniques used. In particular, the adoption of suitable agronomic strategies, in association with careful selection of the species and cultivar, would make it possible to minimize reductions in yield. This regards in particular salinity control in the root zone, especially during germination and the early phenological phases. This can be achieved by increasing irrigation frequency or satisfying the leaching requirement.

Toxic elements

The presence of particular ions in the water can cause phytotoxicity problems – direct toxicity for various physiological processes of the plant or nutritional imbalances – with different levels of tolerance in different plants.

Toxicity problems arise when elements in the irrigation water build up in the plant tissue to such an extent as to cause reductions in yield, independently of the total solute concentration. Elements capable of generating toxicity phenomena are chlorine, sulphur, boron, sodium and ammonium. Toxicity phenomena manifest themselves in a typical fashion for each element and are apparent on old leaves where the buildup is greater.

High sodium (Na) is of concern to growers since it can contribute to salinity problems, interfere with magnesium and calcium availability in the media and cause foliar burns. Sulphur (S) and chlorine (Cl) are essential elements for plant growth. Some crops (cruciferous, leguminous, potatoes) remove significant quantities of sulphur (70 kg ha⁻¹). However, if large quantities of this element are present in the irrigation water, it can damage the crops as a result of direct toxicity. Sulphur is generally found in water in the form of sulphate (SO₄²⁻). However, in reducing environments, sulphates can be converted into sulphides (SO₃⁻) which have higher phytotoxic action; indeed, sulphides cause the precipitation of iron, leading to toxicity symptoms in plants.

TABLE 6
Irrigation water salinity tolerances for different vegetable crops

	0% Yield loss EC (ms/cm)	10% Yield loss EC (ms/cm)	25% Yield loss EC (ms/cm)
Bean	0.7	1.0	1.5
Beetroot	2.7	3.4	4.5
Broccoli	1.9	2.6	3.7
Cabbage	1.2	1.9	2.9
Cantaloupe	1.7	2.6	5.5
Capsicum	1.0	1.5	2.2
Carrot	0.7	1.1	1.9
Celery	1.2	2.3	3.9
Cucumber	1.7	2.2	2.9
Lettuce	0.9	1.4	2.1
Onion	0.8	1.2	1.8
Potato	1.1	1.7	2.5
Radish	0.8	1.3	2.1
Spinach	1.3	2.2	3.5
Squash	2.1	2.6	3.2
Sweet potato	1.0	1.6	2.5
Tomato	0.5	2.3	4.4
Watermelon	1.5	2.4	3.8

Lantze *et al.* (2007), De Pascale *et al.* (2012), Orsini *et al.* (2013)

TABLE 7
Chloride hazard of irrigation water

Chlorides (meq/l)	Chlorides (ppm)	General notes ^a
<2.0	<70	Generally safe for all plants
2.1–4.0	71–140	Sensitive plants usually show slight to moderate injury
4.1–10.0	140–350	Moderately tolerant plants usually show slight to substantial injury
>10.0	>350	Severe problems

^a Most annual crops and short-lived perennials are moderately to highly tolerant to chlorides, and managers can rely on the salinity hazard index to evaluate water-use problems. Trees, vines and woody ornamentals are sensitive to chlorides.

TABLE 8
Chloride tolerance of agricultural crops. Listed in order of tolerance^a

Crop	Maximum Cl ⁻ concentration ^b without loss in yield	
	mol/m ³	ppm
Strawberry	10	350
Bean	10	350
Onion	10	350
Carrot	10	350
Radish	10	350
Lettuce	10	350
Turnip	10	350
Pepper	15	525
Corn	15	525
Potato	15	525
Sweet potato	15	525
Broad bean	15	525
Cabbage	15	525
Celery	15	525
Spinach	20	700
Cucumber	25	875
Tomato	25	875
Broccoli	25	875
Squash, scallop	30	1 050
Beet, red ^c	40	1 400
Squash, zucchini	45	1 575

^a These data serve only as a guideline to relative tolerances among crops; absolute tolerances vary, depending on climate, soil conditions and cultural practices.

^b Cl⁻ concentrations in saturated-soil extracts sampled in the root-zone.

^c Less tolerant during emergence and seedling stage.

Maas, 1990 (Tables 7 and 8)

Chloride (Cl⁻) in water derives from the dissociation of the chloride salts contained in the water and the chlorination (Cl₂) of purified wastewater. Elevated chloride is often associated with an elevated sodium concentration. Cl⁻ is not absorbed by the soil, but moves easily within the circulating solution, from which it is absorbed by the roots, building up in the leaves. At high concentrations, it can interfere with the absorption of nitrates and the transport of organic acids within and between cells. Symptoms of toxicity from chloride appear as burning and drying of leaf tissue (starting at the tips and continuing along the edges), browning, premature yellowing and leaf drop (Table 7).

For most non-woody species, tolerance to chloride can be estimated on the basis of the threshold values given in the salinity tolerance tables (Table 8): assuming that the salinity consists primarily of chloride salts, by multiplying the threshold values in dS/m by 10 we obtain the approximate concentrations of Cl⁻ in mol/m³ in the irrigation water or in the soil saturation extract, which can then be multiplied by 35.4 to calculate the concentrations in g/m³. The potential for chlorides and sulphates to cause damage depends on the sensitivity of the irrigated species and primarily manifests itself when the vegetation is wetted (i.e. sprinkler irrigation).

Boron (B) is an essential element for plant life, but it can be toxic even at very low concentrations. Generally speaking, toxic concentrations of boron are almost exclusively found in soils in arid zones and in well and spring water in geothermal and volcanic regions, while most surface water contains acceptable levels of boron. Significant quantities of boron may be

found in irrigation water due to outflows from residential purification plants, as this element is contained in household detergents in the form of sodium perborate. Levels of 0.2–0.5 mg/litre are considered normal in irrigation water. However, levels of above 0.3 can be harmful to sensitive crops. Irrigation water with a boron content of over 4.0 mg/litre is unsuitable for almost all crops. Plants have different levels of tolerance ranging between the two extreme values. The toxic effects of boron are initially apparent in old leaves in the form of yellowing, chlorotic spots or dried tissue at the tip and edges of the leaf. Plant age also influences susceptibility or the extent of the problem. Seedlings are generally more susceptible than mature plants of the same species (Table 9). Management strategies to minimize boron problems when the water source is high include eliminating boron from the fertilizer sources, increasing the media pH and increasing the calcium level (Table 10).

Well water is sometimes particularly rich in iron (Fe). Acid-loving plants may experience problems when irrigated with ferrous water and are therefore grown in acid soil or substrates. In an acidic environment, iron in the form of ferrous ions does not precipitate, but increases its concentration in solution and can be toxic. Elevated iron levels generally cause aesthetic problems to plants and greenhouse structures. High levels can also lead to an accumulation on irrigation equipment resulting in plugged emitters. Lower levels cause discoloration and higher levels toxicity in plant tissue.

Many other elements react with the soil and cannot be removed by means of leaching, resulting in toxic buildups in the soil and in plants, despite the presence of very low concentrations in the irrigation water. These so-called “trace elements” are generally contained in small quantities in water; they behave in a similar fashion and cause similar problems (Table 11).

Many of these elements (e.g. arsenic, cadmium, cobalt, chromium, copper, mercury, manganese, nickel, lead, tin and thallium) are so-called heavy metals (with a density of over 5 g/cm³). Heavy metal pollution mostly derives from human activities (industry, traffic). Some are essential for many living organisms,

TABLE 9
Boron hazard of irrigation water

Boron concentration	Susceptible crop injury ^a
<0.5 ppm	Satisfactory for all crops
0.5–1.0 ppm	Satisfactory for most crops; sensitive crops may show injury
1.0–2.0 ppm	Satisfactory for semi-tolerant crops; sensitive crops are usually reduced in plant vigour
>2.0 ppm	Suitable only for tolerant plants

^a Plants grown in soil high in lime may tolerate more boron than those grown in non-calcareous soils.

TABLE 10
Limits of boron in irrigation water

Class of water	Crop group		
	Sensitive	Semi-tolerant	Tolerant
Excellent	<0.33	<0.67	<1.00
Good	0.33–0.67	0.67–1.33	1.00–2.00
Permissible	0.67–1.00	1.33–2.00	2.00–3.00
Doubtful	1.00–1.25	2.00–2.50	3.00–3.75
Unsuitable	>1.25	>2.5	>3.75

Permissible limits (boron in ppm).

Maas, 1990 (Tables 9 and 10)

TABLE 11

Recommended limits for constituents in reclaimed water for irrigation (mg/litre)

Constituent	Long-term use	Short-term use	Remarks
Aluminum (Al)	5.0	20	Can cause non-productivity in acid soils, but soils at pH 5.5–8.0 will precipitate the ion and eliminate toxicity.
Arsenic (As)	0.10	2.0	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice.
Beryllium (Be)	0.10	0.5	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.
Boron (B)	0.75	2.0	Essential to plant growth, with optimum yields for many obtained at a few-tenths mg/l in nutrient solutions. Toxic to many sensitive plants (e.g. citrus) at 1 mg/l. Most grasses relatively tolerant at 2.0–10 mg/l.
Cadmium (Cd)	0.01	0.05	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solution. Conservative limits recommended.
Chromium (Cr)	0.1	1.0	Not generally recognized as essential growth element. Conservative limits recommended due to lack of knowledge on toxicity to plants.
Cobalt (Co)	0.05	5.0	Toxic to tomato plants at 0.1 mg/l in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper (Cu)	0.2	5.0	Toxic to a number of plants at 0.1–1.0 mg/l in nutrient solution.
Fluoride (F ⁻)	1.0	15.0	Inactivated by neutral and alkaline soils.
Iron (Fe)	5.0	20.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of essential phosphorus and molybdenum.
Lead (Pb)	5.0	10.0	Can inhibit plant cell growth at very high concentrations.
Lithium (Li)	2.5	2.5	Tolerated by most crops at up to 5 mg/l; mobile in soil. Toxic to citrus at low doses; recommended limit is 0.075 mg/l.
Manganese (Mg)	0.2	10.0	Toxic to a number of crops at a few-tenths to a few mg/l in acid soils.
Molybdenum (Mo)	0.01	0.05	Non-toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels of available molybdenum.
Nickel (Ni)	0.2	2.0	Toxic to a number of plants at 0.5–1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Selenium (Se)	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of added selenium.
Vanadium (V)	0.1	1.0	Toxic to many plants at relatively low concentrations.
Zinc (Zn)	2.0	10.0	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6 or above) and in fine-textured or organic soils.

US EPA, 2004

but become toxic when their concentrations exceed the variable thresholds from element to element and from organism to organism. When using water with high concentrations of heavy metals, the following risks should be considered:

- direct damage caused by phytotoxicity
- buildup of the element in the substrate
- absorption, transfer and buildup in the plant
- diffusion through the food chain

The devices used to control salinity and sodium levels are also used to control toxicity phenomena. As with all salinity problems, toxicity problems are also increased during the period of greatest environmental evapotranspiration demand, meaning that where good quality water is available, it is best to use it during the hottest period of the irrigation season.

Hardness

Calcium (Ca) and magnesium (Mg) are key elements for crops and play a fundamental role in the cation balance of the soil, attenuating the negative effects of sodium. They are generally found in water in the form of ions produced by the dissociation of salts, such as nitrates, chlorides, sulphates, carbonates and bicarbonates. The extent of calcium and magnesium salt content in water is represented by the hardness. Hardness is measured in German and French degrees. One German degree (°dH) corresponds to 10 mg of calcium oxide or 7.19 mg of magnesium oxide per litre of water. One French degree (°f) corresponds to 10 mg of calcium carbonate per litre of water. One French degree therefore consists of 5.6 mg of CaO per litre of water and is therefore around half a German degree. Water hardness is either:

- temporary, caused by calcium and magnesium carbonates (eliminated by boiling the water); or
- permanent, owing to the presence of calcium and magnesium sulphates, nitrates and chlorides.

Water can be classified as:

- soft (0–10 °dH; 0–20 °f)
- moderate (10–20 °dH; 20–38 °f)
- hard (> 20 °dH; > 38 °f)

Temporary hardness influences the general nutritional conditions in the substrate, increasing the pH. This can have a negative effect on acidophilic plants (i.e. some ornamental plants). In very acid substrates, hard water can have a positive effect. The ability of plants to resist irrigation water hardness depends on: the buffer power of the substrate, the initial pH and the amount of water used. Generally speaking, in the case of temporary hardness, the upper resistance limit of plants is about 10 °dH or 18 °f. With total hardness, the upper limit is about 20 °dH or 38 °f. Certain flower crops, such as carnations and chrysanthemums, prosper even when irrigated with water with a permanent hardness of > 20 °dH: in this case, the temporary hardness is under 10 °dH. Vice versa, plants that are very sensitive to hardness can even be damaged by water with a hardness of < 10 °dH. High carbonate and bicarbonate content in irrigation water can block water distribution equipment, especially that used in microirrigation (drip emitters, microsprinklers). If the level of carbonates exceeds the limit indicated in the classification, the need to treat the water either physically or chemically should be assessed.

Measures can be taken to improve hard water, for example by adding acids:

- concentrated sulphuric acid = 10 cm³/m³ of water for every German degree of temporary hardness
- oxalic acid = 22.5 cm³/m³ of water for every German degree of temporary hardness

Hardness can also be eliminated through the use of ion exchange resins. This system eliminates calcium and magnesium from the water and replaces them with potassium, sodium and, in some cases, H⁺ and OH⁻ ions.

Trophic substances

Nitrogen (N) and phosphorus (P) are the main elements in plant nutrition. When surface water is enriched with excessive trophic substances, it can lead to an increase in phytomass productivity in the body of water. This phenomenon, known as eutrophication, can lead to a reduction in the concentration of the oxygen in the water, following the deterioration of the organic substance formed in this way, with alterations in the aquatic biocenosis. This form of water pollution is normally attributed to agricultural activity, due to the release of nitrogen and phosphorus from fertilized fields. This may be true in areas characterized by intense livestock farming and the irrational agronomic use of manure. However, considerable quantities of N and P are also introduced into watercourses by residential and industrial purification plants or, worse still, by untreated waste pipes.

From an agronomic point of view, the presence of nitrogen in the irrigation water can generally be considered an advantage, as it reduces or eliminates the cost of nitrogen fertilization. However, problems can arise with regard to its quantity and distribution over time. It is therefore recommended to adapt the fertilization to the nutrient quantities contained in the irrigation water, in order to avoid excessive availability of nutrients and their release into the runoff water from the irrigated land.

For example:

irrigation water N = 50 mg/litre

irrigation requirement = 200 mm (=200 litre/m²)

50 mg/litre × 200 litre/m² = 10 000 mg N/m² = 10 g N/m² = 100 kg N/ha of nitrogen supplied by means of irrigation, which should be subtracted from the dose to be distributed through fertigation

Excess nutrients in the water and the consequent growth of algae can lead to problems in the water distribution system resulting from the obstruction of the waterflow and the suction lift of the pumps and the blockage of the distributors. In the presence of solid organic matter in suspension, it is advisable to use grit and mesh filters. In some cases, denitrification may be necessary.

Calculated indices

The need to consider the relationships between the concentrations of the various ions has led to the introduction of a number of indices calculated on the basis of analytical data. Herein are described only those of significance for protected agriculture.

Sodium absorption ratio (SAR)

Sodium (Na) is absorbed by colloids in the soil and determines deflocculation with important effects on permeability. However, the risk that the sodium contained in the water is effectively absorbed by the soil is reduced by the presence of calcium (Ca) and magnesium (Mg). The sodium absorption ratio (SAR) is an index designed to assess this risk. It is calculated using the following formula:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

where the concentrations are expressed in meq/litre. Generally speaking, only water with a SAR of more than 10 (or 5 for flower crops, which are much more salt sensitive) is considered risky (Table 12). Some authors have tried to make the sodium risk assessment more sophisticated by introducing parameters and creating adjusted indices, not relevant herein.⁶

Chloride/bicarbonate ratio

The salinity levels of subterranean water vary during the course of the year, and are generally higher during the dry season. One possible cause of this variation is the intrusion of seawater into the watertable – a phenomenon in many coastal areas where water consumption is very high (due to agriculture, industry, tourism etc.). Seawater, unlike subterranean water, is very rich in chloride ions; subterranean

TABLE 12
The sodium hazard of water based on SAR values

SAR values	Sodium hazard of water	Comments
1–10	Low	Use on sodium-sensitive crops must be cautioned
10–18	Medium	Amendments (such as gypsum) and leaching needed
18–26	High	Generally unsuitable for continuous use
>26	Very high	Generally unsuitable for use

Ayers and Westcot, 1985

⁶ Refinement of the SAR called the “Adjusted SAR” (SAR_a) has recently been developed. SAR_a includes the added effects of precipitation of calcium in soils as related to CO₃²⁻ + HCO₃⁻ concentrations. If the SAR_a is less than 6.0 there should be no problems with either sodium or permeability. In the range of 6.0–9.0 there are increasing problems. If the SAR_a is greater than 9.0, severe problems can be expected.

water contains relatively high concentrations of carbonates and bicarbonates. An increase in the chloride ion and carbonate/bicarbonate ion concentration ratio is an indication of possible contamination of the groundwater by seawater.

Ionic balance

In irrigation water, the sum of the concentrations in meq/litre of the positive ions (cations) is equal to that of the negative ions (anions). It is possible to calculate the ionic balance by expressing the concentrations of the main cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) in meq/litre and summing them. Repeating this operation with the main anions (CO_3^{2-} , HCO_3^- , Cl^- , SO_4^{2-} , NO_3^-) produces a similar result; if the results differ significantly, an ion present in large quantities has not been included in the analysis, or an error has been made.

It is important to remember that the sum of the concentrations (in meq/litre) of the cations C (or the anions A) is empirically linked to the EC from the following expression:

$$EC(dS/cm) = 0.1 \times C$$

pH, alkalinity and water acidification

In irrigation practice, especially in fertigation, water is often acidified to reduce incrustations and keep the substrate pH at optimum levels, generally between 5.5 and 6.5 (< 7.0). Although this operation is generally carried out automatically by specific equipment, it is important to be able to calculate the quantity of acid needed to reach the desired pH, as the acids used (nitric, phosphoric and sulphuric) are also fertilizers and it is therefore necessary to know the amount of nutrients added through the acidification process. Rather than the pH of the irrigation water, it is the alkalinity that is important, i.e. the concentration (meq/litre) of the bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. In fact, as the term alkalinity suggests, it is the alkalinity that determines the amount of acid required to correct the pH.

IRRIGATION WATER ANALYSIS: UNITS, TERMS AND SAMPLING

Analysis of irrigation water is crucial for greenhouse production in order to avoid phytotoxicity phenomena for crops, rationalize fertilization (especially in the case of fertigation) and decide whether or not to install a special water treatment plant. Reference should be made to official analysis methods when analysing water.

Sampling

Analysis can be performed at any time of year, but water characteristics may vary noticeably on the basis of seasonal rainfall, especially in the case of surface water sources. If there is no information available about the usual conditions of the well, it is best to carry out at least two analyses in order to investigate any changes to the composition of the water: one during a rainy period and the other during a dry period. It will then be sufficient to repeat the control in a laboratory every

1–3 years, carrying out periodic pH and electrical conductivity (EC) tests with user-friendly portable instruments – considered an essential part of any farm's equipment.

It is very simple to sample irrigation water, following a few basic rules:

- The well must have been made at least a few weeks earlier and must be in regular use; if it has been out of use for some time, it should be used for a few days before sampling.
- Before taking the sample, the water should be allowed to flow for a few minutes.
- A clean polyethylene bottle with a capacity of at least 1 litre (and filled completely) should be used; however, as some measurements may require a larger volume of water, it is recommended to contact the laboratory in advance for more detailed information.
- The sample should be sent to the laboratory as soon as possible, with a label attached including details of the farm and the crop, the name or number used to identify the water source and the type of analysis to be performed. If, for any reason, 1–2 days should pass before sending the sample, it is necessary to contact the laboratory for advice on the best storage methods, which may vary depending on the parameters to be investigated.

Analytical parameters measured

The choice of parameters to be measured by the laboratory (Tables 15 and 16) is the result of a compromise between the need to gather as much information as possible and the cost. As a rough guide, a very detailed analysis (suggested for fertigation

TABLE 13
Parameters used in the evaluation of irrigation water quality

Parameters	Symbol	Unit
<i>Physical</i>		
Total dissolved solids	TDS	mg/l
Electrical conductivity	EC _w	dS/m ^a
Temperature	T	°C
Hardness		mg equiv. CaCO ₃ /l
Sediments		g/l
<i>Chemical</i>		
Acidity/Basicity	pH	
Type and concentration of anions and cations:		
Calcium	Ca ⁺⁺	me/l ^b
Magnesium	Mg ⁺⁺	me/l
Sodium	Na ⁺	me/l
Carbonate	CO ₃ ⁻⁻	me/l
Bicarbonate	HCO ₃ ⁻	me/l
Chloride	Cl ⁻	me/l
Sulphate	SO ₄ ⁻⁻	me/l
Sodium absorption ratio	SAR	
Boron	B	mg/l ^c
Trace metals		mg/l
Heavy metals		mg/l
Nitrate-Nitrogen	NO ₃ -N	mg/l
Phosphate-Phosphorus	PO ₄ -P	mg/l
Potassium	K	mg/l

^a dS/m = deciSiemen per metre in SI Units (equivalent to 1 mmho/cm)

^b me/l = milliequivalent per litre

^c mg/l = milligrams per litre = parts per million (ppm); also, mg/l ~ 640 x EC in dS/m

TABLE 14
Classes of water by main salinity features

Problem	Degree of problem		
	None	Increasing	Severe
<i>Salinity</i>			
EC (mS/cm)	<0.75	0.75–3.00	>3.00
TDS (ppm)	<480	480–1920	>1920
Caused by sodium (SAR _a)	<6.0	6.00–9.00	>9.00
<i>Toxicity from root absorption</i>			
Sodium (SAR _a)	<3.00	3.00–9.00	>9.00
Chloride (me/l)	<4.00	3.00–10.0	>10.0
Chloride (ppm)	<140	140–350	>350
Boron (ppm)	<0.50	0.50–2.00	>2.00
<i>Miscellaneous excess nutrient</i>			
Nitrate-N (ppm)	<5.00	5.00–30.0	>30.0
Bicarbonate (meq/l)	<1.50	1.50–8.50	>8.50

Ayers and Westcot, 1985 (Tables 13 and 14)

TABLE 15

Desirable levels of nutrients and other components of irrigation water

Water quality measurements	Desirable range ^a
pH	5.8–6.0
Alkalinity	0.75–2.6 meq/l CaCO ₃
Electrical conductivity (EC)	<1.5 mS/cm
Hardness	100–150 mg CaCO ₃ /l
Calcium (Ca)	40–100 ppm
Magnesium (Mg)	30–50 ppm
Sodium (Na)	<50 ppm
Sulphate (SO ₄)	<50 ppm
Chloride (Cl ⁻)	<100–150 ppm
Boron (B)	<0.5 ppm
Fluoride (F ⁻)	<0.75 ppm

^a Desirable levels; acceptable levels may be broader.

Will and Faust, 1999

in Table 17) can cost 90–250 euros, or even more, depending on the geographic location and the type of laboratory. The choice is therefore not always easy, and must be made on the basis of:

- previous analytical data;
- the reason for requesting the analysis;
- farm characteristics (species grown, cultivation technique etc.);
- local characteristics.

In simpler terms, chemical water characteristics can be divided into four different categories:

- **pH – electrical conductivity (EC).** EC allows an initial assessment of the water, but is insufficient for an accurate judgement. The EC relates to the overall salt content which, in turn, is linked to the osmotic pressure.
- **Concentration of characterizing substances.** This enables classification of the water on the basis of its effects on the soil/substrate, the crop and the plumbing systems; these parameters should always be measured.
- **Concentration of macro- and micro-elements.** This tells us about the “fertilizing power” of the water and indicates the potential toxicity risks associated with the concentration of micro-elements, which depends on the pH of the water (risks increase as pH decreases). These parameters need to be measured for accurate fertilization management or if the area presents particular risks. The data provided by nearby farms with wells of a similar depth may be very useful.
- **Concentration of toxic substances.** While generally not present in hazardous quantities in water, they can sometimes be a problem. Their use is recommended only if pollution is suspected. Heavy metals may be of geological origin, but they are sometimes the result of human activity.

The meaning of the various parameters is outlined in Table 16. There are other parameters (e.g. concerning the biological hazard) that can be investigated too, but these are not generally considered for irrigation water. In summary:

- Water quality is critical to successful horticulture greenhouse production.
- Appropriate water quality tests should be conducted prior to selecting a greenhouse site.

TABLE 16

Chemical analysis of irrigation water: meaning of the main analytical parameters

Parameter	Chemical symbol or abbreviation	Meaning
<i>Acidity or basicity</i>		
pH		Expresses acidity or basicity of water; 7.0 corresponds to neutrality, lower values indicate acidity and higher values indicate basicity.
<i>Salinity</i>		
Electrical conductivity	EC	Indicate the overall quantity of salts present. The simplest to measure is the EC, which provides an initial assessment of the water quality (for conversion, see Table 3).
Fixed solids or total dissolvedsalts	TDS	
<i>Characterizing substances</i>		
Calcium	Ca ²⁺	Absorbed in considerable quantities by plants and not toxic, even at high concentrations; if present in considerable quantities, they react with carbonates and bicarbonates to form limescale, deposited in the pipes, nozzles and leaves.
Magnesium	Mg ²⁺	
Sodium	Na ⁺	Sum of Ca and Mg concentrations represents total hardness. Absorbed by plants, indispensable at low concentrations; generally a problem because it tends to build up in the soil/substrate with toxic effects for plants, worsening the physical characteristics of the soil.
Chlorides	Cl ⁻	Absorbed by plants, they are indispensable at low concentrations for higher plants, but usually pose a problem because they tend to build up in the soil or substrate with toxic effects for the plants.
Carbonates	CO ₃ ²⁻	A progressive accumulation in the soil or substrate causes the pH to rise. In the presence of calcium or magnesium, carbonate forms insoluble compounds (limescale) which can cause plumbing problems and incrustations on leaves. Carbonates are only present if the pH is over 8.0–8.3. They are also referred to by the term “alkalinity”.
Bicarbonates	HCO ₃ ⁻	
Sulphates	SO ₄ ²⁻	Sulphur (S) is an indispensable for plants and is absorbed, in the form of sulphate, in large quantities. There can be an excessive concentration in the water causing buildups in the soil or substrate, with an increase in salinity. Leaf deposits may form.
<i>Macro- and micronutrients</i>		
Nitric acid	NO ₃ -N	Nutrients absorbed in the largest quantities by plants. While unlikely to reach toxic concentrations, it can be important to know their concentrations in the irrigation water so that this can be taken into account in the fertilization plan, especially if using fertigation.
Ammoniacal nitrogen	NH ₄ ⁺ -N	
Phosphates	PO ₄ ³⁻	Important elements for the life of plants; excessive concentrations form reddish or brownish-red precipitates which can damage equipment and tarnish leaves, with reduced commercial value of the product at low levels, and a marked reduction in leaf development, and thus the development of the entire plant, at high levels.
Potassium	K ⁺	
Iron	Fe	Indispensable for plant life at low concentrations, they can easily reach toxic concentrations, which vary according to the species. They can also cause damage due to buildups on the leaf surface.
Manganese	Mn	
Copper	Cu	
Zinc	Zn	
Boron	B	
Molybdenum	Mo	
<i>Toxic substances</i>		
Anionic tensioactives	MBAS BIAS	Contained in detergents, they may be toxic to plants.
<i>Other metals</i>		
Cadmium	Cd	Some of the so-called “heavy metals”; over certain limits they are toxic to man and plants.
Chromium	Cr	
Nickel	Ni	
Lead	Pb	
Mercury	Hg	Can be toxic over certain concentrations.
Fluoride	F ⁻	
<i>Parameters associated with drip emitter blockage</i>		
Total suspended solids or total suspended matter	TSS TSM	Inorganic (sand, lime, clay) or organic matter that can create problems by blocking the plumbing.

- Water properties may change significantly during the year, particularly as the demand increases on a groundwell and the watertable is lowered.

Table 17 presents the criteria for choosing the appropriate type of analysis. The general suggestions should be adapted to suit the individual situation. However, it is not possible to indicate a suitable analysis type for every situation in advance and expert advice should be sought.

Interpreting a laboratory report

The interpretation of an analysis certificate can appear complex to the layman, for various reasons.

First, it is necessary to identify the “threshold value”, i.e. the concentration above which a substance can become harmful. Cultivated species have different

TABLE 17
Guidelines for choosing the irrigation and water analysis type

Parameter	Initial assessment	Intensive farming	Fertigation	Water treatment system planning
<i>Acidity/basicity; salinity</i>				
pH	•	•	•	•
EC or fixed solids	•	•	•	•
<i>Characterizing substances</i>				
Calcium	•	•	•	•
Magnesium	•	•	•	•
Sodium	•	•	•	•
Chlorides	•	•	•	•
Carbonates/bicarbonate (alkalinity)	•	•	•	•
Sulphates	•	•	•	•
<i>Macro- and micronutrients</i>				
Nitric nitrogen			•	•
Ammoniacal nitrogen			•	•
Phosphates			•	•
Potassium			•	•
Iron	•	•	•	•
Manganese		•	•	•
Copper		•	•	•
Zinc		•	•	•
Boron	o	•	•	•
Molybdenum	o	o	o	o
<i>Toxic substances</i>				
Tensioactives	o	o	o	o
Cadmium, Chromium, Nickel, Lead, Mercury	o	o	o	o
Fluorides	o	o	o	o
<i>Parameters associated with drip emitter blockage</i>				
Suspended solids				•

• = always necessary; o = necessary in zones at risk.

levels of tolerance and the growing technique is also a decisive factor: for example, a given salt content can be dangerous for a greenhouse crop but not for a field crop which is periodically washed by the rain.

Second, irrigation water quality must be assessed by examining the relationship between the various parameters: for example, a given salt content may be tolerated if the ions present are primarily calcium and magnesium, while it may be harmful if sodium and chlorides predominate.

The threshold values in Table 18 (shown separately for greenhouse crops and open field crops) are therefore indicative and are only sufficient for the purposes of an initial assessment: expert knowledge of the farm in question is necessary for an accurate analysis.

Finally, the units of measurement used to express the results may differ, making it difficult to compare different analyses or an analysis and a series of threshold values.⁷

ON-SITE WATER TESTING

Not many farms have even a small laboratory and many do not need one. However, it is indispensable to have at least a pH meter and a conductivity meter to check the pH and EC levels on a regular basis. These are portable instruments, easily available on the market at a wide range of prices, at the lower end affordable for all farms. When using these instruments it is important to follow some fundamental rules so that the readings are reliable.

In summary, analytical testing of irrigation water is an essential part of any rational cultivation method. It must be repeated constantly over time to rule out composition variations which sometimes occur and may have negative effects on the crop. Periodic water pH and EC measurements performed by the farm are an important step in the right direction. Portable instruments for measuring irrigation (or fertigation) water pH and EC are affordable and user-friendly, essential for correct management of greenhouse crops.

Management practices for irrigating with saline or sodic water

If poor quality water is used for irrigation, one or more of the following practices may be necessary to avoid soil problems which will limit crop yields:

- Provide adequate internal drainage. If barriers restrict movement of water through the root zone, water with a moderate sodium hazard ($SAR > 6$) or a salinity hazard ($EC_w > 1.5$) should not be used unless drainage can be provided.

⁷ Table 3 gives the formulae for converting the most commonly used units of measurement and for the most important parameters.

TABLE 18a
Assessment of analysis results

Parameter	Unit	Threshold	Risks in the event of threshold being exceeded					Possible intervention	
			Greenhouse	Open field	Buildup in soil or substrate	Nozzle blockage	Leaf deposits		Toxicity
pH		6.0–8.0	6.0–8.0	6.0–8.0		• (with high pH)		High pH: reduced efficacy of pesticides and fungicides Low pH: corrosive effects	Acidification should be applied in case of high pH in order to reduce nozzle blockage
EC	dS/m (25 °C)	<0.75	<1.50		•		•		Reverse osmosis; dilution with higher quality water
Calcium	ppm	<150					•		Reverse osmosis; acidification; dilution with higher quality water
Magnesium	ppm	<35							Reverse osmosis; acidification; dilution with higher quality water
Sodium	ppm	<50		<150	•		•		Reverse osmosis; dilution with higher quality water
Chlorides	ppm	<50		<200	•		•		Reverse osmosis; dilution with higher quality water
Carbonates, bicarbonates	ppm	<250			•	•	•		Acidification
Sulphates	ppm S	<50		<300	•		•		Reverse osmosis; dilution with higher quality water
Iron	ppm	<1.0		<3.0		•	•		Blockage of membranes due to reverse osmosis Reverse osmosis; dilution with higher quality water; oxidation tanks; Iron removal systems
Manganese	ppm	<0.6		<2.0	•		•	•	Reverse osmosis; dilution with higher quality water; oxidation tanks; manganese removal systems
Copper	ppm	<0.3		<1.0	•			•	Reverse osmosis; dilution with higher quality water

Pardossi *et al.*, 2004

TABLE 18b
Assessment of analysis results

Parameter	Unit	Threshold		Risks in the event of threshold being exceeded					Possible intervention
		Greenhouse	Open field	Buildup in soil or substrate	Nozzle blockage	Leaf deposits	Toxicity	Others	
Zinc	ppm	<0.3	<3.0	•			•		Reverse osmosis; dilution with higher quality water
Boron	ppm	<0.3	<2.0	•			•		Reverse osmosis; dilution with higher quality water
Molybdenum	ppm	<0.05	<0.05	•			•		Dilution with higher quality water
Tensioactives	ppm	<0.5	<0.5	•			•		
Cadmium	ppm	<0.01	<0.01	•			•		
Chromium	ppm	<0.1	<0.1	•			•		
Nickel	ppm	<0.2	<0.2	•			•		
Lead	ppm	<5.0	<5.0	•			•		
Mercury	ppm	<0.002	<0.002	•			•		
Fluorides	ppm	<1.0	<1.0	•			•		Reverse osmosis
Suspended solids	ppm	<30	<30			•	•		Filtration

- Meet the necessary leaching requirement (following overirrigation) depending on crop and EC_w of water. Leaching requirement can be calculated from water test results and tolerance levels for specific crops. This is necessary to avoid the buildup of salt in the soil solution to levels that will limit crop yields. Effective rainfall can be considered part of the leaching requirement.
- Maintain high water availability in the soil. The soil should not be allowed to become more than moderately dry, since the crop cannot remove all the normally available water due to the higher salt content.

TABLE 19
Electrical conductivity (EC) correction factors for the irrigation water sample temperature^a

Temperature (°C)	Correction factor
5	1.61
10	1.41
15	1.25
18	1.16
20	1.11
22	1.06
24	1.02
25	1.00
26	0.98
28	0.94
30	0.91

^a The reference temperature is usually 25 °C.

Pardossi *et al.*, 2004 (Tables 18a and 19)

General rules for using the pH meter

- Read carefully the instructions manual provided with the instrument.
- The reading bulb (electrode) must remain constantly moist. It should therefore be stored in water (not distilled water) or in specific storage solution (it may be sufficient to place a moist ball of cotton wool in the bulb protection cover).
- The calibration should be checked frequently by immersing the electrode in the specific known pH buffer solutions (generally pH 7.0 and 4.0). If the reading differs noticeably from the nominal value (an error of 0.1–0.2 is tolerable for field measurements), it needs to be calibrated again following the instructions in the manual.
- If it takes a long time to get a stable reading, it is recommended to clean the electrode thoroughly using paper soaked in water and washing it in plenty of water (specific wash solutions are also available on the market). If the readings are still unsatisfactory after doing this, it may need replacing.
- Store the instrument in a warm, dry place.

General rules for using the EC meter

- Read carefully the instructions manual provided with the instrument.
- The EC value⁸ depends heavily on the water temperature (Table 19), so much so that when expressing the results it is important to indicate the reference temperature (usually 25 °C). Most of the instruments on the market – including the relatively affordable models – come with an automatic temperature compensation device. This means that the EC and the temperature values are measured and the reading at the reference temperature is provided automatically. If the instrument has this device, the readings can be used without further calculations. If it does not, the temperature needs to be taken manually and the reading needs to be converted (using Table 5) during the calibration phase.
- The calibration should be checked frequently by immersing the electrode in the specific standard solutions (available at different concentrations). If the reading differs noticeably from the nominal value (an error of 0.1–0.2 mS/cm is tolerable for field measurements), it needs to be calibrated again following the instructions in the manual.
- The electrode must be cleaned periodically.
- Store the instrument in a warm, dry place.

⁸ Electric conductivity measurements do not indicate the relative amounts of any specific salt and ion. Additional specific tests typically run by outside laboratories must determine concentrations of specific ions.

- Monitor salt and sodium with saline-alkaline soil tests every 1–2 years. Development of a sodium hazard usually requires time: soil tests for SAR of saturation extract or percentage of exchangeable sodium detect changes before permanent damage occurs; proper management maintains SAR and salinity values steady below danger level. Soil samples should be taken to represent the top 30 cm and the second 30 cm. Occasionally samples should be taken to a depth of 1 metre.
- Add soluble calcium such as gypsum (calcium sulphate) to reduce the SAR to a safe value. Gypsum can be metered into the water at the required rate, or in some cases it can be broadcast annually over the field. If broadcast, apply directly ahead of irrigation or incorporate thoroughly into the tillage layer to avoid crusting problems. If the soil contains free lime, elemental sulphur could be broadcast. The sulphur solubilizes the calcium from the free lime already in the soil. If gypsum is used, the leaching requirement may be increased.
- Use should be restricted to drought periods to supplement below-normal rainfall or when other sources of water are inadequate.

The appropriate combination of practices depends on which hazard or hazards are associated with the water to be used, and the severity of the hazards. Sometimes the risk and cost is too great to attempt using the water. Table 20 provides some help, but expert advice should be sought if the water constitutes a high or very high hazard.

TABLE 20

Sodium hazard of irrigation water based on sodium adsorption ratio (SAR) and electrical conductance (EC_w)^a

	Salinity hazard, EC_w				Expected permeability and management
	0.75 Low	0.75–1.50 Medium	1.50–3.00 High	> 3.00 Very high	
	SAR ^b or SAR _s ranges				
Low	<6	<6	<4	<2	No permeability problems expected.
Medium	6–9	6–8	4–6	2–4	Usually no permeability problems expected except when soils are high in clay and EC_w is high or very high.
High	9–12	8–10	6–8	4–6	Possible permeability problems. Can use on sandy soils if LR is met. May need soluble calcium added if silt loam or finer texture. Monitor by soil test.
Very high	>12	>10	>8	>6	Serious permeability problems expected. Requires added soluble calcium or use only limited amounts as supplement to rain fall or good quality water. Monitor with soil test at the end of each season.

^a To determine sodium hazard, match EC_w value with appropriate column, read down to SAR or SAR_s value, and read sodium hazard in left-hand column (Hergert and Knudsen, 1977).

^b Use SAR_s if water is used to irrigate soils containing free calcium carbonate (lime). Soil pH will exceed 7.0.

CORRECTING WATER QUALITY PROBLEMS

Desalination

Water supplies are becoming increasingly critical, meaning that in some cases saltwater has to be used for irrigation purposes. Rather than taking water from the sea, as in some greenhouse production areas (e.g. in Almería, Spain), it is possible to use wastewater from industrial processes or wells contaminated by seawater infiltrations.

There are numerous desalination techniques, based on different principles:

- Water evaporation (multiple effects, solar evaporation, thermocompression, multiple expansions)
- Freezing (direct freezing process)
- Use of salt-permeable membranes (electrodialysis)
- Use of ion exchange resins (ionic exchange)
- Use of semipermeable membranes (reverse osmosis)

The systems used for agricultural purposes are essentially based on the last two techniques.

Resin exchange equipment can be used to treat small volumes of water (water supply for fog or cooling systems, nebulizers etc.). Their use can range from demineralization of hard water to desalination of saltwater. In practice, the water is channelled through a cationic resin bed with a high cation exchange rate, regenerated with hydrochloric acid (HCl), then through an anionic resin bed with a high anion exchange rate, regenerated with soda (NaOH). After these two passages, the water has a relatively modest salt content, according to the degree at which the process was carried out.

Reverse osmosis technology is used to treat large volumes of water. Although this technology arrived on the market relatively recently, it quickly established itself thanks to the advantages it offered: versatility, excellent performance and ease of use.

In order to explain this process, it must be remembered that when two solutions of different concentration are placed in contact through a semipermeable membrane (permeable to the solvent and not to the solute), the water passes spontaneously from the most diluted solution to the more concentrated solution. The pressure that needs to be exercised on a solution in contact with the pure solvent through a semipermeable membrane in order to stop the flow of solvent towards the solution is called osmotic pressure. If pressure is placed on the more concentrated solution, the solvent flow will be slowed until it comes to a stop and will then be reversed if the pressure is increased. This process, known as reverse osmosis, is used to separate the pure solvent (in this case water) from a

solution. The pressure that has to be applied to achieve reverse osmosis depends on a number of different factors, including the concentration of the solution and temperature. In order to have sufficient waterflow, high operating pressures are used, as the osmotic pressure of seawater is around 22 atm.

Depending on the type of membrane used, and therefore on its efficiency, it is possible to achieve various degrees of desalination, and water with a saline content suitable for industrial or agricultural purposes, or even for human consumption, can be achieved directly. The effectiveness of this very interesting water desalination process essentially depends on the quality of the selective membranes used.

The principle characteristics of membranes for reverse osmosis are:

- high mechanical resistance (kg/cm^2);
- permeability to the solvent (m^3/m^2 per day); and
- high rejection (capacity to oppose the passage of solutes, measured as a percentage of solutes initially contained in the solutions treated and still present after treatment).

The useful life (in reference to operating pressures) of a desalination membrane for reverse osmosis is the time during which it preserves its permeability characteristics, making it possible to keep the waterflow constant at a given degree of purity. It is reduced as substances are deposited on the membranes and by the action of micro-organisms, for which appropriate pretreatments are required.

Mass-produced systems currently available on the market are distinguished primarily by the quality of incoming water they accept, expressed in mg/litre of total dissolved salts (TDS), which vary from 1 500–2 000 mg/litre (low salinity) to 5 000 mg/litre (brackish water), and 15 000 mg/litre (seawater); and by production, which can vary from a few cubic metres to over 1 000 m^3 per day.

pH correction

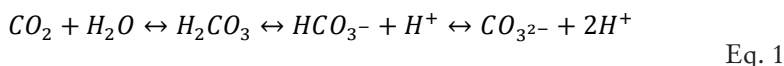
In irrigation, particularly fertigation, it is advisable to correct the pH of the water, especially with hardness $> 20\text{--}30$ °f (200–300 mg/litre of calcium carbonate; 1 °f corresponds to 10 mg/litre). This operation reduces incrustation and the subsequent damage to the irrigation systems themselves, and keeps the pH of the substrate within the values required for normal physiological activity of the roots (growth, absorption of water and minerals) and for adequate availability of nutrients.

Acidification

In conditions typical of Mediterranean greenhouse areas, subterranean irrigation water is generally characterized by high alkalinity, linked to the relatively high

(oversaturation) concentration (equivalent concentration) of the carbonate ion (CO_3^{2-}) and, even more so, bicarbonate ion (HCO_3^-), considering that the former is only present in significant concentrations for pH of over 8.0.

Effectively, the pH of the water is determined by the chemical equilibrium between carbon dioxide (CO_2), carbonic acid (H_2CO_3), the bicarbonate ion (HCO_3^-), the carbonate ion (CO_3^{2-}) and the hydrogen ion (2H^+):



The first and the second dissociation of carbonic acid are characterized by the following equilibrium constants (K):

$$K_1 = \frac{([\text{HCO}_3^-] \times [\text{H}^+])}{[\text{H}_2\text{CO}_3]} = 4.45 \cdot 10^{-7}$$

$$K_2 = \frac{([\text{CO}_3^{2-}] \times [\text{H}^+])}{[\text{HCO}_3^-]} = 4.7 \cdot 10^{-11}$$

therefore $pK_1 = \text{acid dissociation constant, defined as: } -\log_{10}K_1 = 6.35$

therefore $pK_2 = \text{acid dissociation constant, defined as: } -\log_{10}K_2 = 10.32$

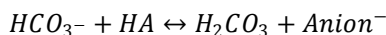
The constant of the second dissociation is decidedly low (as already mentioned, carbonates are effectively only present in water with a pH of over 8.0–8.3) and, in order to simplify the calculations, we can consider the first dissociation only. This is a completely acceptable approximation within the irrigation water pH range. We can therefore calculate the pH as for a buffer solution:

$$\text{pH} = pK_1 + \log([\text{HCO}_3^-]/[\text{H}_2\text{CO}_3]) \quad \text{Eq. 2}$$

As mentioned earlier, the irrigation water is very rich in bicarbonates and carbonates. This moves the chemical equilibrium (Equation 1) to the left and leads to the formation of carbon dioxide, which tends to disperse into the air, consequently subtracting H^+ from the solution and increasing the pH. This explains the pH variations often encountered when a water sample is left in contact with the air for some time, as well as the absence of a close relationship between the alkalinity of the water and its pH.⁹

⁹ The equivalent concentration of one ion in a solution is calculated on the basis of the molar concentration divided by its valence (1 for HCO_3^- , 2 for CO_3^{2-}).

The addition of acid to the water leads to the progressive transformation of carbonates and bicarbonates into carbonic acid, and then into carbon dioxide. The amount of acid needed to reach a certain pH therefore depends on the initial carbonate and bicarbonate concentration, or rather the alkalinity. The acidification reaction is as follows:



Note that the number of acid equivalents $[HA]$, of bicarbonates subtracted from the solution and of carbonic acid formed are equal, therefore:

$$[HCO_3^-] = [HCO_3^-]_{initial} - [HA] \quad \text{Eq. 3}$$

$$[H_2CO_3] = [HA] \quad \text{Eq. 4}$$

We can now take Equation 3; replacing Equations 4 and 2 we have:

$$pH = pK_1 + \log([HCO_3^-]_{initial} - [HA])/[HA]$$

by extracting $[HA]$ we obtain the concentration of acid needed to obtain the desired pH on the basis of the bicarbonate concentration:

$$[HA] = [HCO_3^-]/(1 + 10^{pH-pK_1}) \quad \text{Eq. 5}$$

Equation 5 shows that an acid (H^+) concentration equivalent to about 70 percent of the bicarbonate concentration in the water gives a pH of 6.0.

On the basis of the calculated concentration $[HA]$ and of the characteristics (concentration, density, equivalent weight) of the product to be used, the quantity of acid is calculated using the most common units of measurement in the field:

$$Q = [HA] \cdot EW / (10 \times D \times AC)$$

where:

Q is the quantity of acid (ml/litre or litre/m³) necessary to obtain the desired pH

EW the equivalent weight of the acid

D the density (kg/litre) of the acid

AC its concentration (% w/w)

Chloridric, nitric, phosphoric (considered monoprotic) and sulphuric acid can all be used with great care (add the acid to the water, never the other way round). The most commonly used is nitric acid – less harmful than sulphuric acid and an important fertilizer. The cost of using it as acid is compensated for by the savings in expenditure on nitrogen fertilizers.

Generally speaking, automatic dispensers are used in order to pump a diluted acid solution into the irrigation water. Acids are highly corrosive for steel, concrete and aluminium. It is therefore important to make sure that the acid solution only passes through polyethylene or PVC pipes, and that the dispenser pump is acid resistant. It is advisable not to exceed a concentration of 5 percent in the mother solution, given that acid-based commercial products normally have a much higher concentration. Once again, the acid should be added to the water and never the other way round.

The characteristics of the acids most commonly used in irrigation water acidification are shown in Tables 21 and 22. The Baumé scale (Bé) is also used to express the density of acids, in addition to the centesimal scale (relative density referred to water = 1 000). There are two Baumé scales, for liquids lighter and heavier than water respectively: for heavier (denser) liquids, such as acids, the Bé° increases with the density of the liquid.

TABLE 21

Concentration, density and equivalent weight (EW) of the acids most commonly used in irrigation water acidification

Nitric acid (HNO ₃) EW = 63		Phosphoric acid (H ₃ PO ₄) EW = 98		Sulphuric acid (H ₂ SO ₄) EW = 49	
Concentration (% w/w)	Density (kg/litre; °Bé)	Concentration (% w/w)	Density (kg/litre)	Concentration (% w/w)	Density (kg/litre)
30.0	1.13 (22.1°Bé)	37.0	1.25	25.0	1.18
53.5	1.33 (36.0°Bé)	75.0	1.58	40.0	1.30
57.9	1.36 (38.0°Bé)	85.0	1.70	95.0	1.83
61.0	1.37 (39.3°Bé)				
62.5	1.38 (40.0°Bé)				
65.0	1.39 (40.7°Bé)				
67.0	1.40 (41.5°Bé)				
69.0	1.41 (42.0°Bé)				

TABLE 22

Quantity of acid to be added on the basis of the quantity of bicarbonates present in the irrigation water and the desired pH

Bicarbonate (mg/litre)	pH	Nitric acid	Phosphoric acid	Sulphuric acid
250	5.5	0.248	0.243	0.204
200	5.5	0.198	0.194	0.163
150	5.5	0.149	0.146	0.122
100	5.5	0.099	0.097	0.082
50	5.5	0.050	0.049	0.041
250	6.0	0.195	0.191	0.161
200	6.0	0.156	0.153	0.129
150	6.0	0.117	0.115	0.097
100	6.0	0.078	0.077	0.064
50	6.0	0.039	0.038	0.032

Many acidification devices inject acid into a tank rather than onto a pipe: contact with the air facilitates the formation of carbonic acid, and carbon dioxide is therefore exchanged with the atmosphere. This allows more accurate regulation of the final pH.

Addition of bicarbonates

In the case of surface water, rainwater or desalinated water, it may be necessary to add small concentrations (approx. 100–150 mg/litre) of sodium bicarbonate (NaHCO_3) or potassium bicarbonate (KHCO_3), in order to boost the buffer power (that is to say the capacity to keep the pH relatively constant) of the irrigation or fertigation water, which is determined by the carbonic acid/bicarbonate system. Bicarbonate addition is a simple process which makes it possible to avoid sudden marked drops in the pH (even to levels below 4.0), which could be caused by an imprecise dose of acid or physiological acidification of the roots.

Filtration

There are three main types of filter on the market, useful for suspended solid matter:

- **Mesh filters.** The water is filtered through a stainless steel and/or nylon mesh with a gauge that varies in size depending on the particles to be filtered. This technology generally uses filters with 70–200 mesh (number of holes/inch), equivalent to a hole diameter of 210–75 μm . Suitable for water free from organic matter, but containing fine and very fine sand. Filters can be cleaned manually or automatically by inverting the flow.
- **Vortex or hydrocyclone desanders.** The water is forced into a vortex. The centrifugal force separates matter with a higher specific weight (earth and sand) which accumulates at the bottom of the filter. Suitable for water rich in sand and large particles, but not for organic matter lighter than water. Must be used in combination with mesh filters.
- **Sand or grit filters.** The filter element consists of layers of sand and/or gravel in large containers. It is combined with mesh filters and used to eliminate organic matter, but requires frequent and constant cleaning.

TABLE 23

Water purification methods and their applications

	Total dissolved solids	Bicarbonate and carbonate	Calcium and magnesium	Dissolved iron and manganese	Oxidized iron and manganese	Borate	Fluoride
Reverse osmosis	X	X	X	X		X	X
Deionization	X	X	X	X		X	X
Anion exchange		X				X	X
Water softening (cation exchange)			X	X			
Activated carbon							X
Activated alumina							X
Oxidation/Filtration				X			
Chelation				X			
Filtration					X		
Acid injection		X					

Pardossi *et al.*, 2004**CONCLUSION**

Greenhouse irrigation water comes from a number of different sources and so its quality varies. Some general rules are however valid:

- Before cultivation, water should be tested by an accredited laboratory.
- Simplified on-site water testing may be conducted using portable instruments (e.g. pH and EC meters).
- Knowing your water quality allows you to plan for water treatments to avoid problems such as poor plant growth, clogged watering pipes, staining and other undesirable effects of poor water quality.
- Problems with water quality may have a chemical basis (e.g. acidic or alkaline water or concentrations of certain elements) or be of a physical nature (e.g. temperature, suspended solids).
- Optimal pH of irrigation water is 6.5–7.5. Water with pH 6.0–8.5 can be used, whereas pH < 5 or > 8.5 is considered anomalous for irrigation purposes.
- Water alkalinity is the capacity to change or resist a change in pH. Optimal alkalinity range of 0.75–2.6 meq/litre, being generally smaller when plants are younger.
- Salinity directly affects plant capability to absorb water and photosynthesize. Optimal water present EC < 0.75 mS/cm (or dS/m). Plant growth is generally not affected up to 2.0 mS/cm (or dS/m), although different responses among species and cultivars may be found. Yield decreases are generally experienced when water EC is above 2.0 mS/cm (or dS/m). Moreover, also the composition of salts should be assessed, since some elements may present specific toxicity in plants.
- Low quality waters may be corrected through desalination, pH correction, acidification, addition of bicarbonates and filtration.

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10. Soil fertility and plant nutrition

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INTRODUCTION

Modern vegetable growers want to operate in an environmentally sound way, but how can vegetables be grown with minimal losses to the environment? Answers are first required to basic questions: What is soil fertility and what role do plant nutrients play in vegetable production? What are typical amounts and forms of plant nutrients in soils? What nutrient forms do crops take up? What are the input and output of plant nutrients to and from soils? What factors affect conversion between forms? What variations in plant nutrient availability occur between soils?

To optimize plant nutrition, it is necessary to ask: Which plant processes are particularly sensitive to plant nutrients? How do nutrients move within the plant? How do plant nutrients affect growth, yield and quality of the produce? What will be the crop's nutrient requirement throughout the growing season? What will be the total requirement of the crop for nutrients? What is the expected trend of nutrient concentration in the different organs during the growing season?

Decision-making in fertilization strategy requires answers to other specific questions: When is soil and plant nutrient status considered sufficient? What are the critical values or ranges for plant nutrients? What type of soil and plant analyses are best for making fertilizer recommendations? What will be the supply of nutrients from the soil? What are the natural and man-supplied sources of plant nutrients? Which principles of plant nutrient management does the grower need to understand and apply to ensure unrestricted crop growth, product quality and minimum environmental pollution? How effective will any application of manure and fertilizer be and, therefore, how much should be applied?

Plant nutrition and fertilization practices are important components of the GAP protocols. To contribute to successful application of GAP, this chapter gives a short overview of soil fertility, nutrient functions in plant metabolism, plant nutrient requirements, fertilization management, nutrient availability in the root zone and the impact of nutrient imbalances on plant growth and yield.

SOIL FERTILITY

Soil fertility is a complex feature and is crucial to the productivity of agricultural soils. It deals with the ability of soil to provide nutrients for crop production drawing both from its own reserves and external applications.

A definition of soil fertility that focuses on short-term productivity is based on the capacity of soil to immediately provide plant nutrients. When soil fertility is considered in terms of the highest practical level of productivity, the focus is mostly on physical and chemical aspects of soil.

A definition of soil fertility inclusive of long-term sustainability must consider the complex interaction between the biological, chemical and physical properties which affect directly or indirectly nutrient dynamics and availability.

In greenhouses, the management of soil fertility is of utmost importance for optimizing crop nutrition on both a short-term and a long-term basis to achieve sustainable crop production. It is related to the greenhouse climate and the complex interaction involving the many factors contributing to the biological, chemical and physical properties of the soil:

- Biological factors can be both beneficial (microbial population, mycorrhizal fungi, *Rhizobium* bacteria) and harmful (soil-borne pathogens).
- Physical properties of importance for greenhouse production are soil texture and structure (Box 1), the soil volume that can be explored by the roots, and its water-holding capacity.
- Chemical factors contributing to soil fertility include nutrient status and soil organic matter (Box 2), soil pH (Box 3) and cation exchange capacity (Box 4).

Many of soil's biological, chemical and physical properties change comparatively slowly, but under greenhouse conditions (especially in Mediterranean areas) changes occur more rapidly due to the climatic conditions (e.g. high temperatures) and the high agronomic inputs (e.g. water, fertilizers) needed to sustain the intensive cultivation of the soils.

Like all soils, greenhouse soils contain natural reserves of plant nutrients, but only a small proportion are readily available for crops (nutrients in the soil solution or adsorbed onto the exchange complex). Less available forms (organic matter or insoluble minerals) must be solubilized or mineralized to be taken up

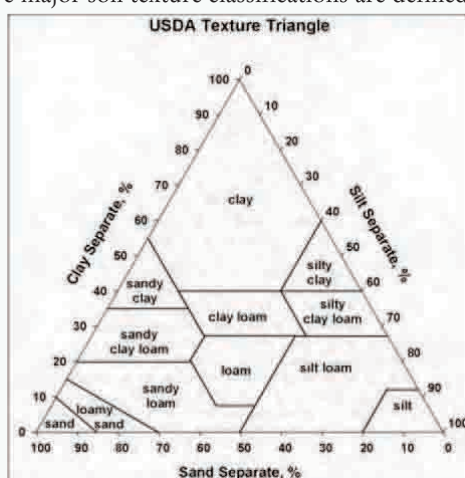
BOX 1

Soil texture and structure

Soil texture is the tool used to describe the grains and mineral particle sizes in a soil. Particles are grouped according to their size into three soil separates:

1. sand separates with a diameter of 0.05–2 mm
2. silt separates with a diameter of 0.002–0.05 mm
3. clay separates with a diameter of < 0.002 mm

Soil texture classification is based on the fractions of soil separates present in a soil and twelve major soil texture classifications are defined by the USDA:



1. sand
2. loamy sand
3. silt
4. sandy loam
5. loam
6. silt loam
7. sandy clay loam
8. clay loam
9. silty clay loam
10. sandy clay
11. silty clay
12. clay

Soil structure is determined by how individual soil grains clump or bind together and aggregate, and describes the arrangement of soil pores between them. Soil structure has a major influence on water and air movement and availability, biological activity and root growth and crop performance.

by the crops. These processes are usually slow, but are accelerated by the high temperatures found in greenhouses.

The nutrients dissolved in the soil's water are mainly nitrate, magnesium, potassium and sulphates. The quantity of these nutrients is normally low and not sufficient for greenhouse crops which have high nutrient requirements (Sonneveld and Voogt, 2009). Soil solution used in greenhouses differs greatly from that used for crops in the open air, mainly because of the higher application of fertilizers and the greater extraction of nutrients by plants.

The nutrients adsorbed in the exchange complex (mainly calcium, magnesium and potassium) are potentially good indicators of the total amount of nutrients in the soil. In order to be available for the crops, they must be desorbed and enter the

BOX 2

Soil organic matter (SOM)

Soil organic matter (SOM) is approximately 1–3% by weight and 12–15% by volume. It can be divided into three general pools:

- 1. living biomass of micro-organisms
- 2. well-decomposed organic matter
- 3. highly stable organic material

Surface crop residues are generally not included as part of soil organic matter.

When organic material is incorporated into the soil, some components (e.g. proteins) degrade quickly (in a period of weeks to months), while others (e.g. lignins) decay very slowly. This rather stable organic material is called humus and roughly corresponds to SOM.

SOM has a key role in both plant nutrition (release of nutrients, energy supply for soil micro-organisms, formation of the nutrient exchange complex) and soil structure (improvement of porosity and soil aeration, increase of water-holding capacity in sandy soils, limiting of compaction and erosion of heavy soils).

SOM is generally estimated indirectly as the result of the concentration of organic carbon times 1.724.

Rating	SOM (%)		
	Sandy soils (1, 2, 4) ^a	Loamy soils (5, 6, 7, 8) ^a	Clay and silty soils (3, 9, 10, 11, 12) ^a
Very low	< 0.8	< 1.0	< 1.2
Low	0.8–1.4	1.0–1.8	1.2–2.2
Medium	1.5–2.0	1.9–2.5	2.3–3.0
High	> 2.0	> 2.5	> 3.0

^a For soil texture classification, see Box 1.
CRPV, 2010

soil solution. Those nutrients which are less available are in the form of organic or mineral-insoluble material; they move with the help of soil micro-organisms. It is very important to analyse the soil at the beginning of the growing period (Plate 1) to understand the nutrient content now and in the future. It is thus possible to plan well the fertilization strategy, and nutrient deficiencies can be avoided.



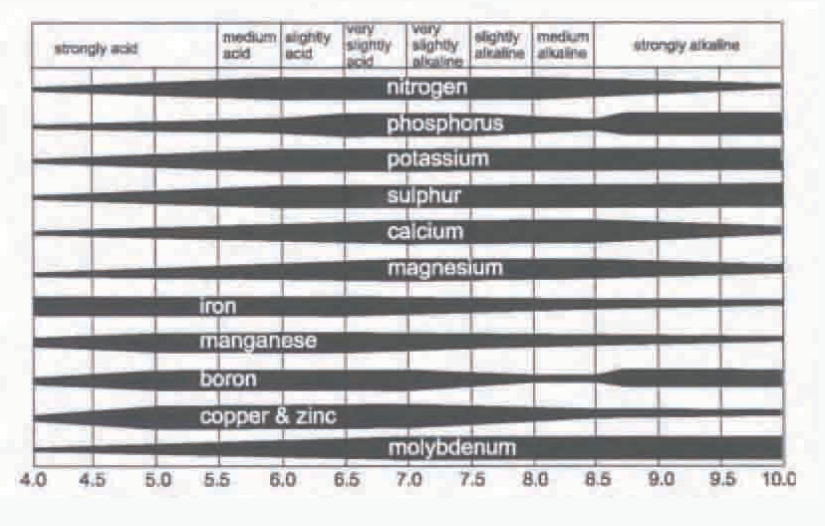
Plate 1
Quick chemical analysis of soil extracts provides estimates of soil nutrient concentration that are valuable for fertilization management

With regard to nutrient availability, it should be noted that the roots occupy a small part of the total soil volume and that the nutrients have reduced mobility; the physical conditions of soil where the roots are developed (soil structure) are therefore very important. Other important factors include temperature, irrigation and microbial activity.

BOX 3

Soil pH

Soil pH is a measure of the acidity or basicity in soils. It ranges from 0 to 14: 0 most acidic, 14 highly basic, 7 neutral. Soil pH is considered a master variable in soils as it controls many chemical processes. It specifically affects plant nutrient availability by controlling the chemical forms of the nutrient. The optimum pH for most plants is 6–7.5, however, many plants have adapted to thrive at pH outside this range. Soil reaction affects also microbial activity.



BOX 4

Cation exchange capacity (CEC)

CEC expresses the maximum quantity of total cations a soil can hold, at a given pH value, for exchanging with the soil solution. CEC is a measure of fertility, nutrient retention capacity and the capacity to protect groundwater from cation contamination. It is expressed as milliequivalent of hydrogen per 100 g (meq+/100 g), or centimol per kg (cmol+/kg). The numeric expression is coincident in both units.

Rating	CEC (meq +/100 g)
Low	< 10
Medium	10–20
High	> 20

PLANT NUTRITION

Plants are capable of synthesizing, through the process of photosynthesis, all organic compounds needed for their life (e.g. amino acids, lipids and vitamins). Therefore, unlike animals, plants need only inorganic compounds to cover their nutritional needs. A total of 16 inorganic elements are essential for plant growth and development (Table 1). More than half of these elements (in particular: carbon C, hydrogen H, oxygen O, nitrogen N, phosphorus P, potassium K, sulphur S, calcium Ca and magnesium Mg) are needed in relatively large quantities and are, therefore, known as “macronutrients” (or major nutrients). Other elements (in particular: iron Fe, manganese Mn, zinc Zn, copper Cu, boron B, molybdenum Mo and chlorine Cl) are also indispensable for plant growth, but they are needed in much smaller quantities and are, therefore, termed “micronutrients” (or trace elements).

Of the nine plant macronutrients, C is taken up from the air as CO₂ through the leaf stomata and fixed into organic compounds via photosynthesis, while H and O are constituents of the water. In most cases, sufficient quantities of Ca, Mg and S (in the form of sulphates) are available in the soil and irrigation water and, therefore, these macronutrients are not included in standard crop fertilization schemes. Thus, in most cases, only three macronutrients – N, P and K – need to be supplied by growers to the crops via fertilization. With regard to the seven plant micronutrients, these are present in sufficient quantities in most arable soils but their availability to crops depends on the soil properties, especially the pH.

In soil-grown greenhouse crops, some of the nutrient requirement is applied as a base-dressing. This is particularly the case with P, which is somewhat immobile in the soil. In contrast, N, which is highly soluble in water in the form of nitrate and ammonium salts, is supplied to the crop after planting. In many greenhouses, water-soluble fertilizers are applied to the crop after planting through the irrigation system (fertigation). Fertigation is generally automated in order to save

TABLE 1
Essential nutrients and forms in which they are taken up by plants

Macronutrient	Chemical form	Micronutrient	Chemical form
Carbon (C)	CO ₂	Iron (Fe)	Fe ²⁺
Oxygen	H ₂ O	Manganese (Mn)	Mn ²⁺
Hydrogen	H ₂ O	Zinc (Zn)	Zn ²⁺
Nitrogen (N)	NO ₃ ⁻ , NH ₄ ⁺	Copper (Cu)	Cu ²⁺
Phosphorus (P)	H ₂ PO ₄ ⁻ , HPO ₄ ²⁻	Boron (B)	H ₃ BO ₃
Sulphur (S)	SO ₄ ²⁻	Molybdenum (Mo)	MoO ₄ ²⁻
Potassium (K)	K ⁺	Chlorine (Cl)	Cl ⁻
Calcium (Ca)	Ca ²⁺		
Magnesium (Mg)	Mg ²⁺		

TABLE 2

Ranges of nutrient concentrations in fertigation solutions supplied in greenhouse crops (mg litre⁻¹)

Nitrogen (N)	50–200	Iron (Fe) ^a	1.0–4.0
Phosphorus (P) ^a	10–50	Manganese (Mn) ^a	0.5–2.0
Sulphur (S)	–	Zinc (Zn) ^a	0.2–0.5
Potassium (K)	100–250	Copper (Cu) ^a	0.02–0.06
Calcium (Ca) ^a	50–150	Boron (B) ^a	0.2–0.5
Magnesium (Mg) ^a	20–50	Molybdenum (Mo) ^a	0.02–0.10

^a Routinely not included in the fertigation scheme unless inadequate availability is indicated by soil analysis.

on labour and fertilizers and improve plant mineral uptake. As a result, water-use efficiency can increase considerably if the water and nutrient doses are correct.

In many parts of the world, including most Mediterranean countries, many greenhouse growers still determine fertilizer application rates by a “rule of thumb”. In most cases, this practice results in excessive application rates for nitrogen, phosphorus and potassium. In some cases, excessive application of one or more nutrients is accompanied by inadequate supply of other nutrients, thereby exacerbating the incidence of single-nutrient toxicities or deficiencies, or even resulting in multinutritional disorders. To prevent such problems, balanced fertilization schemes based on knowledge of plant nutrient requirements and soil nutrient reserves, which should be determined by chemical soil analysis, are needed. Optimal fertilizer application rates for each particular nutrient can thus be estimated by deducting the soil reserves from the total plant requirements.

NUTRIENT MANAGEMENT AND ENVIRONMENTAL RISK

Traditional management of nutrients in greenhouse production is based on the assumption that plant growth is not limited by water and nutrient uptake. In greenhouses, if fertilization is not well managed in soil-grown crops (e.g. excessive amounts of fertilizer, fertilizers distributed only at planting without splitting nitrogen rate throughout the growing season), a water surplus is often necessary to avoid soil salinization and to keep soil moisture high. Additional fertilization is then necessary to compensate for nutrient losses caused by leaching (Kläring, 2001). The main factors causing N-NO₃ leaching in greenhouse crops in Almería (Spain) are manure and excessive irrigation during the first weeks after planting (Thompson *et al.*, 2007).

In Mediterranean countries, soilless cultivation has been developed mainly as open system, where excess nutrient solution is required to drain the substrate. In this kind of system, the irrigation strategy provides a quantity of nutrient solution that is 30 to 50 percent in excess of the crop requirements in order to avoid salt buildup near the root zone (Ehret *et al.*, 2001). Nitrogen contained in nutrient solution discharges (leachates) from soilless horticulture is a major contributor to groundwater pollution and eutrophication in greenhouse crops (Antón, 2004;



Plate 2

Tomato crop with soilless crop systems where leachate is collected and recirculated

Pardossi *et al.*, 2006; Muñoz *et al.*, 2008a). In north European countries, annual N losses from open soilless cultivation approach 1 tonne ha⁻¹ (Duchein *et al.*, 1995). Closed or recirculating soilless hydroponic systems (Plate 2) give the lowest environmental impacts (Antón, 2004): while they can significantly reduce fertilizer runoff, they cannot eliminate it, as the exhausted nutrient solution has to be ultimately collected and treated at the end of the crop cycle. Intermediate situations, for example cascade crops, reduce the consumption of water and fertilizers and the environmental impact in certain categories (e.g. eutrophication and climate change) (Muñoz *et al.*, 2008b). However, closed systems involve greater installation and running costs, need a high degree of automation and technical skill, and their economic viability is a question of debate in southern Europe (De Pascale and Maggio, 2005; Massa *et al.*, 2010).

Life cycle assessment (LCA) is an objective and transparent methodology to quantify and assess a product's environmental burden (Audsley, 1997). For greenhouse crops, a reduction in fertilizer input can significantly reduce the environmental impact from a Mediterranean greenhouse in terms of air acidification, depletion of abiotic resources, eutrophication, greenhouse effect and photochemical oxidant formation (Antón *et al.*, 2005; Muñoz *et al.*, 2008a). Diminishing their use in greenhouse production decreases the depletion of natural gas, for example, in the production of KNO₃, K₂SO₄ and (NH₄)₂PO₄. A reduction in the use of nitrogen fertilizers can reduce the emission of methane during their production, and can significantly decrease photo-oxidant formation. Nitrous oxide and other greenhouse gases produce a significant impact in the greenhouse effect category, as they are released mainly during the production of fertilizers such as KNO₃, (NH₄)₂PO₄ and NH₄NO₃.

NITROGEN

Nitrogen (N) is essential for all life processes in plants. It is a structural component of all proteins including enzymes, which are involved in all chemical reactions that together constitute the processes of growth and development. Furthermore, N is an important component of the nucleic acids (DNA, RNA) and is a central part of chlorophyll. It is present in plant alkaloids, in some B complex vitamins, including thiamine (B1), riboflavin (B2), niacin (B3), pantothenic acid (B5) and

folic acid (B9), and in many other substances (in the vegetation of field crops N accounts for approximately 2–4 percent of the dry matter weight). Nitrogen stimulates vegetative growth and ensures high rates of flower formation, fruit-set and assimilation inflow into developing fruits. Insufficient N supply – manifested in uniformly chlorotic leaves – severely restricts plant growth and yield.

In vegetable crops, the yield response to N is dramatic and farmers tend to apply N fertilizers to maximize yields, rather than risk underfertilizing and suffering revenue losses.

Nitrogen sources

Soil minerals do not contain N, or its content is negligible. Hence, unlike other plant nutrients, N does not become available to the plant via the weathering of inorganic soil particles.

Atmosphere

The earth's atmosphere is the major reservoir for N (air is 78 percent N₂ gas) and is the ultimate source of N. Atmospheric N becomes available to the plant through fixation. It can be fixed by specific bacteria, by reaction with oxygen at high temperatures (during electrical storms, in combustion processes and through oxidation by sunlight), and in fertilizer production.

Large amounts of atmospheric N can be used by legumes through their symbiotic association with *Rhizobium* bacteria, which inhabit the roots of the plants. These bacteria have the capacity to incorporate N₂ from the air and convert it to a form available to the plant – a process known as biological N fixation. Residue of any legume crop left after harvest adds N to the soil system; when plant material decomposes, N is released.

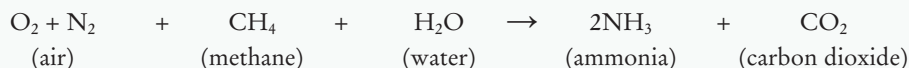
Atmospheric N oxidized by lightning and in combustion processes (atmospheric fixation) generally returns to the soil surface, either with rain or snow, or in a dry form (wet and dry atmospheric deposition). The latter can account for twice as much N as the former. In most European countries, the annual rate of atmospheric deposition of N is extremely variable and can reach 40 kg ha⁻¹ or more (Laegreid *et al.*, 1999). However, in a greenhouse, where rainfall does not occur and air changes are quite slow, atmospheric deposition accounts for an almost insignificant proportion of the N in the soil. In greenhouse systems, the most important source of N is the irrigation water, an N input which every grower should take into account when planning N fertilization.

Almost all commercial N fertilizers are derived from atmospheric N. They originate from ammonia (NH₃), which, in turn, is made by combining atmospheric N and hydrogen. The hydrogen mostly comes from the reaction between water and methane (Box 5).

BOX 5

How N fertilizers are obtained

The reaction to obtain N fertilizer is:



Ammonia may be used as a fertilizer (anhydrous ammonia), or as a starting point in the manufacture of other nitrogen fertilizers. It can be combined with carbon dioxide to form urea $[\text{CO}(\text{NH}_2)_2]$. Oxidation of ammonia produces nitric acid (HNO_3). This combines with ammonia to give ammonium nitrate (NH_4NO_3).

Soil organic matter

Soil organic matter (SOM) is also a major source of N (over 90 percent of soil N is associated with SOM). SOM in the top 25 cm of soil represents a stock of about 1 700–1 800 kg N ha⁻¹, of which only 1–3 percent is decomposed on an annual basis in open air crops (Vos and MacKerron, 2000). The net result is that a small amount of the SOM is mineralized each year during periods when soil temperature and water content favour microbe and soil animal activity. The higher the temperature, the more quickly mineralization occurs, and in greenhouses (with frequent watering and high temperatures), SOM mineralization accelerates, increasing N availability but causing more rapid depletion of soil organic N. The mineralization rate can also be increased by tillage; shallow and light tillage is preferred to preserve the SOM. Returning crop residues to the soil or introducing other organic sources such as animal manures or compost may replenish the SOM.

Although crop residues represent a significant potential source of N (Scharpf, 1991), in greenhouse cropping systems the aerial part of most crops is rarely incorporated into the soil, but is removed to avoid the risk of spreading diseases. Only root residues contribute to the soil N; the amount of N can nevertheless be relatively high if legumes have been grown.

Animal manure

Animal manures are another potentially important source of N. The quantity of N supplied by manure varies with type of livestock (species, age and diet), handling (e.g. bedding materials), application rate and method of application. As a general indication, cattle manure may contain 5–18 kg N/tonne. About half of this nitrogen is converted relatively quickly (some months) to forms available to plants. Lesser amounts are gradually converted over a longer period. Decay occurs more rapidly in greenhouses than in the open field as a consequence of the higher

temperatures. Since the N form and content of manures varies widely, analysis of the manure is recommended to improve N management.

Compost

Compost generally supplies proportionately less mineral N than crop residues and manures. During the composting process, easily degraded fresh material breaks down. Some of the N is volatilized, and the organic matter that remains is relatively resistant to mineralization. Nevertheless, applying compost year after year indirectly enhances the supply of organic nitrogen by increasing the soil's humus content.

Nitrogen transformations and utilization by plant

Once N enters the soil, various transformations condition its availability to plants and influence the potential losses to the environment. Plants take up N either as NO_3^- or as NH_4^+ . Usually NO_3^- dominates over NH_4^+ in soils, and most crops take up more NO_3^- than NH_4^+ . Together they are known as soil mineral N. Urea nitrogen [$\text{CO}(\text{NH}_2)_2$] may also be taken up by plants to some extent and at certain growing stages (Tan *et al.*, 2000). However, most of the urea supplied to soil as fertilizer is first converted into NH_4^+ and then taken up by plants either in that form, or as NO_3^- after nitrification. Nitrogen bound in organic compounds must first be converted into NO_3^- or NH_4^+ through mineralization before being taken up by plants. Not only the roots, but also the plant leaves have the capacity to absorb N; spraying foliage is therefore another method of N application.

Organic material in the soil, including crop residues, manures and composts, is digested by a succession of soil animals and micro-organisms which gradually break down large molecules to smaller molecules and, finally, to carbon dioxide, water and minerals. Mineralization refers to the process of breakdown of organic matter in the soil, and it results in the release of ammonium (NH_4^+). The mineralization rate depends on soil moisture conditions, soil acidity, temperature and microbial activity. Bacterial growth itself is directly related to soil temperature and water content; therefore, the rate of mineralization and NH_4^+ formation increases in greenhouses as the temperature is high. On the other hand, soil disinfection (frequently carried out in greenhouses) to reduce the microbe population slows down the mineralization processes.

Soil micro-organisms need N to prosper and multiply. As a consequence, when the organic matter incorporated in the soil is poor in N, soil organisms need to absorb NH_4^+ from the soil – or, to a lesser extent, nitrate (NO_3^-) – in order to be able to utilize the organic material. This conversion of soluble forms of N to organic forms is called N immobilization. These forms are temporarily tied up in microbial tissue, to be mineralized when the organisms die and are themselves subjected to degradation. Whether or not immobilization of N takes place depends on the carbon to nitrogen ratio (C:N ratio) of the organic material. If the C:N ratio

exceeds 20 (e.g. cereal straw), nitrogen is immobilized during degradation. When the C:N ratio is lower than 20 (e.g. vegetable and legume residues), degradation of the material results directly in mineralization of N.

In well-drained soil, NH_4^+ is transformed to NO_3^- by bacteria. This process is fairly rapid and is called nitrification. These bacteria are relatively inactive at lower soil temperatures and therefore one will find larger $\text{NH}_4^+/\text{NO}_3^-$ ratios in winter and early spring than in summer, and in the open field than in the greenhouse.

Once applied, fertilizer N is subject to the same transformations as other sources of N; for example, urea [$\text{CO}(\text{NH}_2)_2$] readily hydrolyses to produce NH_4^+ , and is then converted into NO_3^- through nitrification. NH_4^+ and NO_3^- are the ultimate forms of N taken up by plants from the soil solution and through their roots.

Nitrogen losses

Nitrogen may be lost from the soil-plant system via various routes, including volatilization, denitrification and leaching. In the open field, N may also be lost through soil erosion (mainly NH_4^+), but in the greenhouse this loss mechanism is practically null.

Volatilization

Volatilization is the process whereby soil N forms are converted to ammonia (NH_3) gas. If the NH_3 is formed at the soil surface, N may be lost to the atmosphere. This loss mechanism is limited to surface-applied N sources, and is commonly associated with surface-applied urea. Nevertheless, other ammonium fertilizers (e.g. ammonium sulphate) and manures may undergo this process. Loss of N from volatilization dramatically increases when soil pH is high (≥ 7), air temperature high and soil surface moist, and when there is a lot of residue on the soil. In such conditions, 10–25 percent of broadcast urea can be lost through volatilization (Laegreid *et al.*, 1999). Considering the climate and soil conditions generally found in greenhouses, surface spreading of fertilizers is not recommended. Volatilization losses are virtually eliminated if the N fertilizer is lightly incorporated into the soil.

Denitrification

Denitrification occurs when soils are nearly water-saturated: roots and soil organisms consume oxygen quickly, and anaerobiosis occurs. In anaerobic conditions, most soil organisms (including roots) cease activity; but some micro-organisms are specifically adapted to such conditions; some have the capacity to extract oxygen from soil NO_3^- . During this process, N_2 gas is formed and escapes to the atmosphere.

Soil should not be waterlogged for denitrification; if the top layer of soil is unsaturated and the deeper layer saturated (e.g. depth of 15–30 cm, where much of

the N is present), considerable N losses can occur (Revsbech and Sorensen, 1990). Denitrification requires a sufficient amount of organic matter to provide energy for bacteria. The process proceeds rapidly when soils are warm and become saturated for 2 or 3 days.

In addition to N_2 gas, traces of nitrous oxide (N_2O) are formed. This is a cause for environmental concern, because it is a persistent and potent greenhouse gas and does not return to the soil surface as part of atmospheric nitrogen deposition.

In greenhouses, when irrigation is managed correctly and soil saturation is avoided, N losses through denitrification are negligible; on the other hand, under inappropriate conditions, losses can be significant.

Leaching

Volatilization and denitrification are processes promoted by biological transformations; loss of NO_3^- by leaching is a physical event. Leaching is the process whereby NO_3^- moves downwards in the soil profile with soil water.

Leaching of NO_3^- is possible because NO_3^- is an anion (negatively charged ion) and is repelled by negatively charged surfaces of clay minerals and SOM. This keeps NO_3^- in the soil solution and it moves in whatever direction the soil water moves. In contrast, NH_4^+ is a cation (positively charged ion) and it is attracted and held by negatively charged soil particles; therefore, NH_4^+ does not move a lot in the soil. It is evident that soils have a higher binding capacity for cations than anions, but some anion-binding capacity does exist. However, other anions (e.g. phosphate and sulphate) are bound in preference to NO_3^- .

Leaching takes place when water inputs exceed the water used by the crop. In such conditions, water drains in the soil profile, dragging NO_3^- with it below the root zone, where it may enter either ground- or surface water. Leaching represents both a loss of N from the system and an environmental concern. Nitrate-rich surface water exerts ecological effects in non-agricultural ecosystems (e.g. eutrophication), while nitrate-rich groundwater cannot readily be used to produce drinking water (Council of European Communities, 1991).

Sandy soils have a higher potential to leach NO_3^- than fine-textured soils, as they have a lower water-holding capacity and the water moves more easily through them.

A deep and extensive root system enables crops to take up N efficiently and minimizes the risk of leaching. The extent of root development and the amount of N needed to produce a satisfactory yield depends on the crop. Many vegetables have shallow roots and a high N demand, and consequently nitrate leaching from vegetable production can be substantial.

PHOSPHORUS

Phosphorus (P) is essential for energy transfer and storage in plant metabolism. Through phosphorylation reactions, P is bound in carbohydrates, nucleic acids, nucleotides, phospholipids, coenzymes and storage compounds, such as phytins. Due to its essential role in energy metabolism, phosphorus is required for photosynthesis, respiration and biosynthesis of several organic compounds, including nucleic acids and sugars. Therefore, sufficient availability of P in the soil is crucial for high yields in greenhouses.

Phosphorus is very mobile in the plant: deficiencies are visible on older leaves, as P moves away to satisfy the needs of new growing tips. Deficient leaves have only about 0.1 percent P by dry matter. Recently matured leaves of most vegetables contain 0.25–0.6 percent P on a dry weight basis. A shortage of P slows the expansion of the older leaves, which curl towards the underside, and it causes a reddish coloration of the petioles and leaves.

Phosphorus sources

Phosphorus is found naturally in water and soils, as well as in all living organisms. In soils, many P compounds exist, in both inorganic and organic forms. Inorganic P ranges from 50 to 75 percent of total soil P and is usually associated with aluminium (Al), iron (Fe) and calcium (Ca) compounds of varying solubility and availability to plants. Organic P compounds range from readily available plant residues and micro-organisms within the soil to stable compounds that have become part of soil organic matter. In cultivated soils, P is present in abundance (1 100 kg/ha), but most of it is not available to plants (15 percent of total soil P is in available form). In practical terms, P in soils can exist in three “pools”: solution, active and fixed P.

Solution P pool

The solution P pool is very small and usually in orthophosphate form ($\text{H}_2\text{PO}_4^{-1}$ or HPO_4^{-2}), but small amounts of organic P may exist as well. Plants only take up P in orthophosphate form via an active energy-requiring process. The solution P pool is important because it is the pool from which plants take up P. A growing crop quickly depletes the P in the soluble P pool if the pool is not continuously replenished.

Active P pool

The active P pool is P in the solid phase, and it is relatively easily released to the soil solution. As plants take up phosphate, the concentration of phosphate in the solution decreases and some phosphate from the active P pool is released. Because the solution P pool is very small, the active P pool is the main source of available P for crops. The ability of the active P pool to replenish the soil solution P pool in a soil is what makes a soil fertile in terms of phosphate. The active P pool contains the following:

- inorganic phosphate adsorbed to particles in the soil;
- phosphate that reacted with elements such as calcium or aluminium to form soluble solids; and
- organic P that is easily mineralized.

Soil particles can act as a source or a sink of phosphate to the surrounding water, depending on conditions: the amount of phosphate adsorbed by soil increases as the amount of phosphate in solution increases and vice versa.

Fixed P pool

The fixed P pool of phosphate contains inorganic phosphate compounds that are very insoluble and organic compounds that are resistant to mineralization by micro-organisms in the soil. Phosphate in this pool may remain in soils for years without being made available to plants and may have very little impact on fertility. The inorganic phosphate compounds in this fixed P pool are more crystalline in their structure and less soluble than compounds in the active P pool.

Phosphorus transformations and utilization by plant

Some slow conversion between the fixed P pool and the active P pool occurs in soils either by plant roots or by soil micro-organisms through secretion of organic acids (e.g. lactic, acetic, formic, fumaric and succinic acids) (Richardson and Simpson, 2011). Soil micro-organisms may also release soluble inorganic phosphate into the soil via decomposition of phosphate-rich organic compounds (mineralization). Solubilization of phosphate by plant roots and soil micro-organisms is substantially influenced by various soil factors, including pH, moisture and aeration. Many phosphate-solubilizing micro-organisms are found in close proximity to the root surfaces and can enhance phosphate assimilation by higher plants. Mineralization occurs in most soils (more in acidic to neutral soils with high organic P content) and is favoured by high temperatures, but it is usually too slow to provide enough P for crop growth.

Certain micro-organisms, especially bacteria, assimilate soluble phosphate and are useful for cell synthesis (P immobilization) (Richardson and Simpson, 2011). Temporarily tied up in microbial tissue, they are eventually mineralized when the organisms die and are subject to degradation.

As phosphate ions enter soil solution, they generally react by adsorbing to soil particles or by combining with elements in the soil, such as calcium (Ca), magnesium (Mg), aluminium (Al) and iron (Fe), and forming compounds that are solids and precipitate (P fixation). The mechanisms for P fixation are complex and involve a variety of compounds.

In alkaline soils (pH > 7.3), Ca is the dominant cation (positive ion) that reacts with phosphate and decreases its solubility and availability. In acidic soils, Al and

Fe are the dominant ions that react with phosphate. Aluminium is most active at a pH of 5.0–5.5. Iron is especially active below pH 4.0 where phosphate is strongly fixed. Of the three processes, P is relatively more available to crops when it is fixed by Ca; P fixation is, therefore, of less concern in alkaline than in acid soils. Maintaining soil pH at 6–7 generally results in the most efficient use of phosphate. Soils in warmer climates (i.e. in greenhouses) are generally much greater fixers of P than soils in more temperate regions.

Phosphorus losses

Phosphorus is a somewhat unique pollutant: it is an essential element, has low solubility, and is not toxic itself, but may have detrimental effects on water quality at quite low concentrations.

Several chemical properties of soil P have important implications for the potential loss of P to ground- and surface water. Most soils have a good capacity to retain P. Adsorbing to soil particles or P fixing occurs rapidly and, therefore, phosphate tends to move through the soil very little, usually just a few centimetres in any single season. As a result of rapid adsorption and fixation, phosphate does not leach – or very little over a long period of time – and is not a potential hazard with regard to contamination of groundwater supplies. However, increasing the phosphate in soils results in increased levels of phosphate in soil solutions. This will generally result in small but potentially significant increases in the amount of phosphate in water passing over or through soils. Movement is slow but may be increased by rainfall or irrigation water flowing through the soil.

POTASSIUM

Potassium (K) has many important regulatory roles in plant development: synthesis of lignin and cellulose, used for formation of cellular structural components; regulation of photosynthesis; and production of plant sugars, used for various plant metabolic purposes. It controls water loss from plants and is involved in overall plant health; it contributes as principal cation to cell turgor and electrochemical compensation of organic anions in the plant cells. K also participates as cofactor or stimulating agent in more than 50 enzymatic systems. Therefore, both the K requirements of plants and the K concentrations in plant tissues are very high. Given the high K requirements of plants, adequate application of K is a prerequisite for high yield and quality in greenhouse crops.

Potassium is highly mobile through the phloem; deficiency symptoms therefore appear in older leaves and severe K deficiency causes necrosis of the old leaves.

An inadequate supply of K may considerably degrade fruit flavour and results in fruit ripening disorders, while optimum K availability improves fruit colour. A relatively high supply of K enhances quality attributes (e.g. titratable acidity, fruit dry matter content and total soluble solids content) in tomato

and other fruit vegetables grown in greenhouses, considerably improving fruit flavour. Furthermore, in tomato, a high K supply would appear to increase the concentration of β -carotene and lycopene, desirable for their ability to trigger a protective mechanism. An adequate supply of K enhances fruit firmness and consequently shelf-life. On the other hand, excesses of K should be avoided to prevent antagonistic restrictions in Ca and Mg uptake.

Potassium sources, utilization by plant and losses

Potassium is a common element in nature, constituting about 2.3 percent of the earth's crust. Clay minerals are soil's main source of K, but much is present as part of insoluble mineral particles and inaccessible to plants. Plants use only exchangeable potassium located on the surface of soil particles or potassium dissolved in the soil water, often amounting to less than 100 mg K kg⁻¹ soil. There are three forms of K in the soil:

- Unavailable K is contained within the crystalline structure of micas, feldspars and clay minerals. Plants cannot use K in these insoluble forms. Over long periods, these minerals weather or break down releasing K as available K ion (K⁺). This process is far too slow to supply the K needs of greenhouse crops.
- Slowly available K or fixed K is trapped between the layers of certain kinds of clay minerals; plants cannot use much of this K in a single growing season. However, the supply of fixed K largely determines the soil's ability to supply K over extended periods of time.
- Readily available K or exchangeable K is dissolved in soil water or held on the surface of clay particles. As plants take up K⁺ from the soil solution and the concentration of K in the soil solution drops, it is restocked from the exchangeable fraction adsorbed on mineral surfaces and the equilibrium is re-established.

Potassium is absorbed readily and in large quantities by an active uptake process. Once in the plant, K is very mobile and is transported to young tissues rapidly.

Deficiency symptoms appear first on lower leaves as a marginal flecking or mottling. Prolonged deficiency results in necrosis along the leaf margins and plants can become slightly wilted. Deficient plant leaves usually contain less than 1.5 percent K.

Since clay and organic matter particles hold potassium ions in an exchangeable or available form, potassium does not leach from silty or clayey soils. Some leaching may take place in very sandy soils because sandy soils do not contain enough clay to hold the potassium.

SULPHUR, CALCIUM, MAGNESIUM

- Sulphur (S) is a structural element in plant tissues: a constituent of two essential amino acids (cysteine and methionine) and many other compounds, including thiamine, coenzyme A, lipoic acid and biotin.
- Calcium (Ca) is a constituent of cell walls and cell membranes. Ca contributes to the hydrolysis of ATP and phospholipids, acting as cofactor in some enzymatic systems. It is a counteraction for inorganic and organic anions in the vacuole, and the cytosolic Ca^{2+} concentration is an obligate intracellular messenger and coordinates responses to numerous developmental cues and environmental challenges.
- Magnesium (Mg) is the building block of chlorophyll and is both an enzyme activator and a constituent of many enzymes. It plays a role in the following processes: sugar synthesis; starch translocation; plant oil and fat formation; nutrient uptake control; nitrogen fixation in legumes. Magnesium is also important for energy transfer, since it is involved in many phosphorylation reactions.

In well-managed, fertile greenhouse soils with normal pH levels, the Ca, Mg and S requirements of greenhouse crops are covered by the soil reserves. In exceptional cases, the availability of Mg and, less frequently, that of Ca in the soil may also be insufficient, depending on soil properties, composition of applied irrigation water and average year precipitation. In particular, levels of available Ca are likely to be insufficient only in acidic, sandy or organic soils.

Sulphur, calcium and magnesium sources, utilization by plant and losses

Sulphur

Most soil sources of S are found in organic matter and are therefore concentrated in the topsoil or plough layer. Elemental S and other forms as found in soil organic matter and some fertilizers, are not available to crops. They must be converted to the sulphate (SO_4^{2-}) form to become available to the crop. This conversion is performed by soil micro-organisms and therefore requires soil conditions that are warm, moist and well drained to proceed rapidly. The sulphate form of S is an anion (negative charge) and is, therefore, leachable.

Sulphur is absorbed mainly as SO_4^{2-} . It is not very mobile in the plant, and deficiency therefore generally begins in the new growth. Deficiency symptoms consist of a general yellowing of the upper leaves. Plant leaves usually contain between 0.2 and 0.5 percent S on a dry-weight basis – a range similar to that for P. Plants can generally tolerate quite high levels of S in the growing media; this is one of the reasons for which sulphur-containing materials are widely used to supply nutrients such as Mg and micronutrients, and S deficiency is thus not very common in greenhouse vegetable crops.

Calcium

Calcium is the fifth most abundant element in the earth's crust and is widely found in nature. Very severe Ca deficiency occurs in crops when soil tests reveal exchangeable Ca to be less than 0.5 meq/100 g.

Calcium, unlike most elements, is absorbed and transported by a passive mechanism. The transpiration process of the plants is a major factor in the uptake of Ca. Once in the plant, calcium moves towards areas of high transpiration, such as the rapidly expanding leaves. Most of the uptake of Ca occurs in a region just behind the root tip – important for greenhouse vegetable culture, because growers must keep healthy root systems with plenty of actively growing root tips. Root diseases will severely limit calcium uptake in the plant.

Calcium moves very slowly in the plant; therefore, deficiency symptoms appear first on new growth. Ca deficiency causes necrosis of the new leaves or leads to curled, contorted growth. Calcium concentrations in normal, most recently matured leaves are between 1.0 and 5.0 percent.

Since Ca movement in the plant is related to transpiration, it follows that environmental conditions that affect transpiration also affect Ca movement. Therefore, it is important to consider irrigation and greenhouse environment control in the overall Ca fertilization programme. In addition, uptake of Ca can be affected by other ions, such as NH_4^+ , Mg^{2+} and K^+ . These cations can compete with Ca for uptake by the root. These competing nutrients should not be supplied in excess of the plant's requirements.

Magnesium

Magnesium is a component of several primary and secondary minerals in the soil, which are essentially insoluble as far as agriculture is concerned. These materials are the original sources of the soluble or available forms of Mg. Magnesium is also present in relatively soluble forms, and is found in ionic form (Mg^{2+}) adhered to the soil colloidal complex. The ionic form is considered to be available to crops.

Magnesium is absorbed by the plant in lower quantities than Ca. The absorption of Mg is also highly affected by competing ions, such as K^+ , Ca^{2+} and NH_4^+ . Unlike Ca, Mg is mobile in the plant and deficiencies appear first on the lower leaves. Deficiency of Mg occurs in the form of intervenialchlorosis, which can lead to necrosis of the affected areas. On tomato leaves, advanced Mg deficiency leads to a mild purpling of the affected areas.

Mg is usually found in concentrations of 0.2–0.8 percent in normal leaves. Conditions leading to deficiency include poorly designed fertilizer programmes supplying too little Mg or ones supplying excess K, Ca or ammonium N.

MICRONUTRIENTS

Seven elements are referred to as micronutrients, because they are required in small amounts – usually a few parts per million (ppm) in the plant tissue. Many research activities are addressing the relationships between micronutrient provision to plants and associated crop growth; trace elements, such as zinc, manganese and copper, are increasingly recognized as essential when aiming for better yields (Gianquinto *et al.*, 2000; Mann *et al.*, 2002; Rashid and Ryan, 2004; Gupta, 2005). There are various studies suggesting that better micronutrient supply to crops might result in more vigorous seedlings, lower vulnerability to plant diseases and, possibly, also improved drought resistance (Frossard *et al.*, 2000; Bouis, 2003).

An inadequate supply of one or more micronutrients can impair crop growth, restrict yields, reduce quality and enhance susceptibility to disease. Intensive cropping can increase the demand for micronutrients to a level higher than the soil can supply. Micronutrients are also important for soil bacteria and deficiencies can diminish the normal rate of soil processes such as mineralization of organic matter or N fixation.

Most metallic micronutrients, in particular iron (Fe), zinc (Zn) and copper (Cu), are involved in redox reactions contributing to energy transfer within or between enzymatic systems. They are involved in the major metabolic functions of plants, in particular photosynthesis, respiration, nitrogen fixation and nutrient assimilation.

- Iron is involved in the biochemical reactions that form chlorophyll and it is part of one of the enzymes responsible for the reduction of $\text{NO}_3\text{-N}$ to $\text{NH}_4\text{-N}$. Other enzyme systems, such as catalase and peroxidase, also require Fe.
- Copper is a component of several enzymes in plants and is part of a protein in the electron transport system in photosynthesis.
- Zinc is involved in the activation of several enzymes in the plant and is required for the synthesis of indoleacetic acid (IAA), a growth regulator.
- Manganese (Mn), which remains in cationic form in plant cells, is essential for the activation of several key enzymes involved in photosynthetic O_2 evolution and other metabolic functions, including dehydrogenases, decarboxylases and peroxidases.

Although the Fe, Zn, Cu and Mn requirements of plants are quantitatively low, their shortage results in severe metabolic disturbances due to their involvement in the central metabolic functions of plants.

- Knowledge of boron (B) functions is limited because B appears to have secondary effects in plant nutrition. The most important physiological effects of B in plants are on the structural integrity of some polysaccharides in the cell walls and on membrane function, as well as a stimulation or inhibition of specific metabolic pathways.

- Molybdenum is a constituent of only two enzymes in plant metabolism: nitrate reductase and xanthine dehydrogenase. It is also a constituent of nitrogenase, an enzyme contained in symbiotic bacteria (*Rhizobium*), and contributes to symbiotic fixation of atmospheric N_2 in bean and other legumes.
- Chlorine (Cl) plays a role in the evolution of O_2 during photosynthesis and might function as a counter ion in K fluxes involved in cell turgor.

Micronutrient sources and utilization by plant

Most soils contain sufficient amounts of metallic micronutrients, specifically Fe, Mn, Zn and Cu, but their availability for plants may be inadequate, resulting in deficiencies if the pH in the rhizosphere is very high.

There are major differences between crops in terms of their micronutrient requirements and sensitivity to deficiency. Micronutrients are often applied with NPK fertilizers, but when deficiency symptoms are visible, salts of micronutrients dissolved in water are sprayed onto the crop foliage.

The most frequent problem at excessively high pH levels (e.g. in calcareous soils) is Fe deficiency. The best way to cope with this problem in the long term is to adjust the soil pH. On the other hand, an excessively low soil pH may induce toxicities of certain metallic micronutrients, especially Mn. If the pH of the greenhouse soil is lower or higher than the optimal range, it is recommended to carry out chemical analysis of the micronutrient concentrations in the leaves: if the concentration of any micronutrient is not optimal, a foliar micronutrient application may be beneficial, even where there are no visual deficiency symptoms, because even a latent deficiency may reduce yield.

Iron

Iron can be absorbed either as Fe^{2+} via an active process, or from Fe chelates which are organic molecules containing sequestered Fe. Uptake depends on the form of Fe, and adequate uptake depends on the ability of the root to reduce Fe^{3+} to Fe^{2+} . Iron chelates are soluble and help keep Fe in solution for uptake. The uptake of the whole chelate molecule is low and Fe is usually removed from the chelate prior to uptake.

Iron is not mobile in plants and the first symptoms appear on the new leaves in the form of interveinal chlorosis resulting from a drastic reduction in the leaf chlorophyll content, that may progress to bleaching and necrosis of the affected leaves. Normal leaves contain 80–120 ppm Fe on a dry-weight basis.

Conditions leading to Fe deficiency are inadequate concentrations of Fe in the nutrient solution, cold media or alkaline media conditions (pH > 7.0).

Manganese

Manganese is absorbed as Mn^{2+} ions and the uptake is affected by other cations (e.g. Ca and Mg). Manganese is relatively immobile in the plant and deficiency symptoms appear on the upper leaves. The symptoms of deficiency of Mn are similar to those for Mg (except that with Mg deficiency they appear on the lower leaves of the plant). Mn deficiency results in interveinalchlorosis; however, the chlorosis is more speckled than with Mg deficiency. A normal concentration of Mn in leaves ranges from 30 to 125 ppm for most plants.

High concentrations of Mn can be toxic to plants. Toxicity consists of marginal leaf necrosis in many plants. Concentrations of Mn in the order of 800–1 000 ppm can lead to toxicity in many crops. Excess Mn in the nutrient solution reduces uptake of Fe. Situations leading to deficiency are mostly related to inadequate Mn supply in the solution or to competition effects of other ions.

Zinc

Zinc uptake is thought to be an active process and can be affected by concentration of P in the media. Zn is not highly mobile in plants. The most characteristic visible symptoms of Zn deficiency are stunted growth (due to shortening of internodes) and decreased leaf size. These symptoms are often combined with leaf epinasty (downward curling of leaf blade), mottling interveinalchlorosis and necrosis.

Normal leaves contain 25–50 ppm Zn. High concentrations of Zn can lead to toxicity where root growth is reduced and leaves are small and chlorotic. Zinc deficiency can be increased by cold, wet growing media or by media with a very high pH or with excessive P.

Copper

Copper is absorbed by plants in very small quantities. Uptake appears to be an active process and is strongly affected by Zn and pH. Copper is not highly mobile in plants but some Cu can be translocated from older to newer leaves. The normal level of Cu in plants is in the order of 5–20 ppm. Copper deficiency of young leaves leads to chlorosis and some elongation of the leaves. Excess Cu, especially in acidic media, can be toxic.

Boron

Boron uptake by plants is not well understood. It is not mobile in the plant and seems to have many uptake and transport features in common with Ca. Deficiency results in growth inhibition and necrosis of the apical meristems and young growing points (e.g. buds, leaf tips and margins), while boron toxicity imposes leaf chlorosis and necrosis symptoms.

The sufficiency range for boron is narrow and requires careful monitoring. Normal leaves contain 20–40 ppm B, while high levels may result in toxicity.

Boron deficiency in greenhouses is likely to occur when the soil B concentration is lower than 1.5 mg g^{-1} of dried soil.

Plants need only small amounts of B; supplying excessive B from fertilizer solutions or from foliar sprays leads to toxicity.

Molybdenum

Molybdenum is absorbed as molybdate MoO_4^{2-} and uptake is suppressed by sulphate. Tissue contents of Mo are usually less than 1 ppm.

Due to the limited metabolic functions involving Mo, the plant requirements for this nutrient are very low and, therefore, a shortage of Mo in greenhouse crops is rare. Deficiency first appears in the mid leaves and older leaves; they become chlorotic and the margins roll. Unlike other micronutrients, Mo deficiency occurs mostly under acidic conditions.

Chlorine

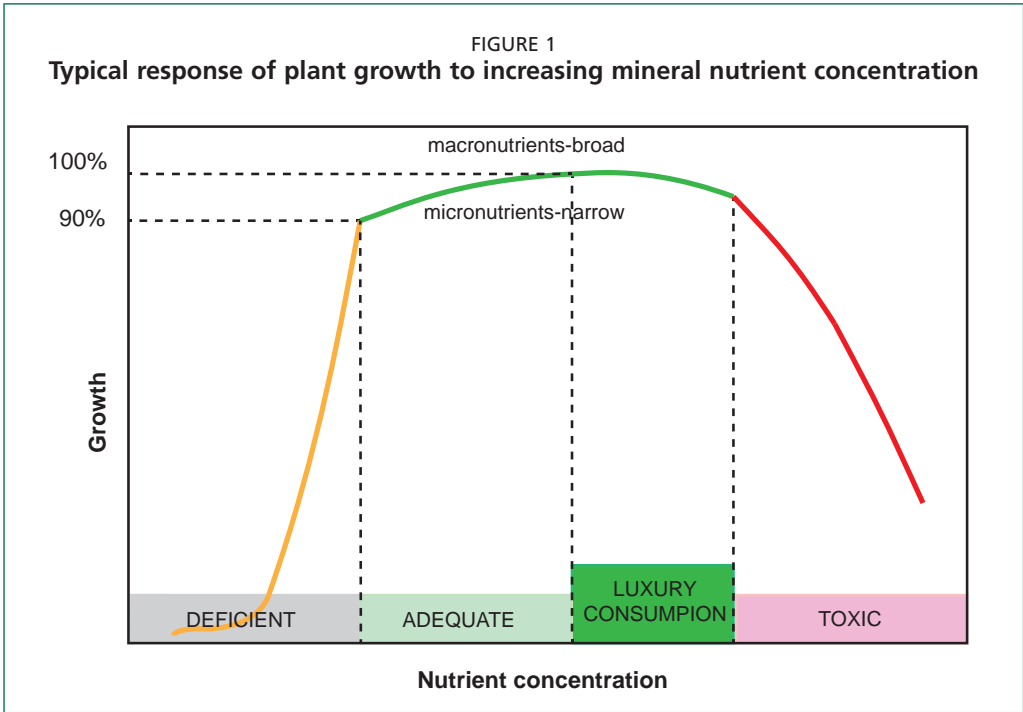
The plant requirements for chlorine are very low and Cl exists in abundant quantities in the earth's crust and also in fertilizers and water; therefore, a shortage of Cl in commercial greenhouse crops is highly unlikely. However, Cl availability in the root environment over and above the plant's requirements may be beneficial, since Cl is utilized by plants as an osmolyte for cell turgor and may improve fruit quality.

SEASONAL CHANGES IN CROP NUTRIENT REQUIREMENTS

The rate of crop mineral uptake and the mutual ratios by which different elements are absorbed by the roots are influenced by the environment (light, temperature and humidity) and vary considerably during the growing season, especially in long-cycle crops, such as fruit vegetables and perennial ornamental plants (rose, gerbera etc.). Indeed, variations in mineral uptake are observed also on a shorter time scale, for example during the 24-hour period, but they are less relevant for the practical management of fertilization.

Many other factors influence the uptake of nutrients, in particular their concentrations and those of other elements (synergistic or antagonist effect), as well as pH, total salinity and moisture in the growing medium. However, the rate of nutrient uptake is driven principally by the demand associated with plant growth – although the actual uptake may increase when there is a luxury consumption of nutrients, or decrease when the formation of specific plant materials takes place with the contribution of stored nutrients.

Luxury consumption occurs when the crop absorbs nutrients without having a corresponding increase in yield (Figure 1). In addition to waste of fertilizers, there are other potential drawbacks: lush growth; impairment of flower and fruit



formation; increased susceptibility to pests, diseases and fruit ripening disorders; worsening of harvested fruit quality (e.g. compositional and textural changes); and, in some crops, accumulation of free nitrates in edible organs, which are harmful to human health.

Remobilization of stored nutrients is limited in herbaceous crops, like greenhouse vegetables, and plays an important role only in conditions of severe nutrient starvation, which are not realistic in well-managed greenhouse crops. A growth-dependent process, mineral uptake is influenced by the rate of photosynthesis and, therefore, it increases with radiation, provided the temperature and other growing conditions remain favourable. Table 3 shows how the uptake rate for water, N and K increases with irradiance. As the increment was

TABLE 3
Maximum uptake rates of nitrogen, potassium and water in indeterminate tomato plants grown under greenhouse conditions in different periods; uptake concentrations for nitrogen and potassium

Period	Uptake rate per plant (mg or ml h ⁻¹)			Uptake concentration (mg litre ⁻¹)	
	N	K	Water	N	K
March	8.1	15.7	43.2	0.188	0.363
June	13.7	25.6	140.9	0.097	0.182

Adams, 1987

higher for water compared with nutrients, the uptake concentration (i.e. the ratio between the elements and the water absorbed by the crop) decreased considerably when the plants were grown at higher light intensity.

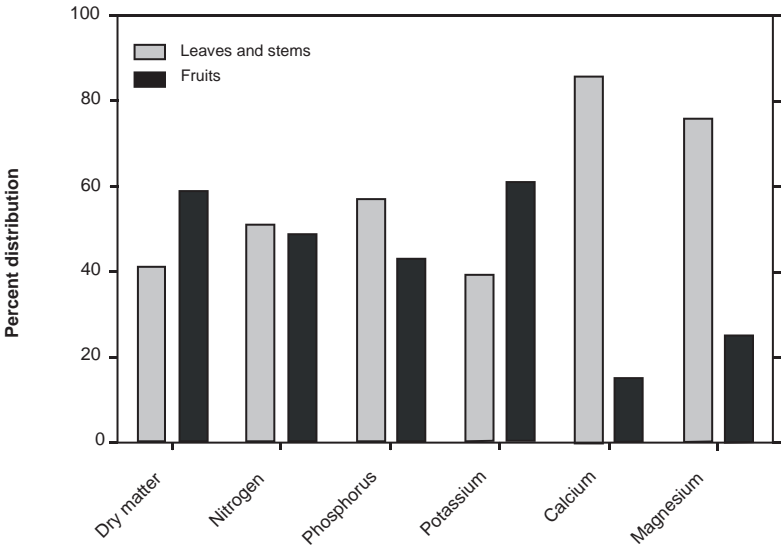
Nutrient uptake concentration is a parameter used by some authors (Sonneveld, 2000; Savvas, 2002; Carmassi *et al.*, 2007; Sonneveld and Voogt, 2009; Massa *et al.*, 2011) to model the crop uptake of both nutritive and non-essential ions (e.g. Na and Cl). Crop models based on the concept of uptake concentration have been criticized (e.g. Le Bot *et al.*, 1998; Silberbush and Ben-Asher, 2001), because water and nutrient uptake are independent processes, despite the reciprocal influence, and thus the uptake concentration of different nutrients is difficult to predict. On the other hand, in many species the variation in ion uptake concentration is much less pronounced than the daily uptake rate (Sonneveld and Voogt, 2009; Carmassi *et al.*, 2007; Gallardo *et al.*, 2009). This happens because the rate of water uptake, which is dominated by leaf transpiration, responds promptly to the changes in crop dimensions (i.e. in leaf area) and environmental conditions, especially radiation. Therefore, the uptake concentration is often used for the management of fertigation in substrate culture (Gallardo *et al.*, 2009; Sonneveld and Voogt, 2009), although it is necessary to consider the remarkable effect of radiation on nutrient uptake concentration. In fact, uptake concentration decreases with high radiation input as plant transpiration increases more than growth-driven mineral demand.

The major reason for seasonal variation of crop mineral uptake, however, is ontogeny, which includes both growth and development and leads to the formation of different tissues and organs, each with its own mineral composition.

Major changes occur as a result of the transition from vegetative to reproductive development. The nutrient concentration of reproductive organs (in particular fruits) is quite different from that of vegetative organs. Consequently, the allocation of different nutritive elements to vegetative and reproductive organs does not match the partitioning of dry matter (Figure 2), resulting in significant variation in the mutual ratios of the nutrients absorbed by vegetative and fruiting plants.

For the definition of a fertilization programme and the interpretation of the tissue analysis results, the concentrations of many nutrients in leaves and other organs vary with physiological age. In general, the contents of N, P and K decline as the plant ages, while those of Ca, Mg, Mn and B often increase. Therefore, the optimum concentrations of mineral nutrients are generally lower in older plants than in younger plants. On the other hand, nutrient levels, in particular N, can be enhanced temporarily in mature plants as the result of a sudden increase in the nutrient availability in the root zone, for example, as a result of top-dressing or fertigation. Table 4 shows the progressive reduction of the critical concentration

FIGURE 2
Percent distributions of dry matter, nitrogen, phosphorus, potassium, calcium and magnesium in above-ground parts of a tomato crop



Data refer to greenhouse tomato grown at University of Pisa (Italy) in soilless culture for about six months from early spring to mid-summer; fruit yield was 20.3 kg m⁻² from 13 trusses.
A. Pardossi and D. Massa, unpublished

(i.e. the minimum concentration allowing the maximum plant growth) of macronutrients in tomato leaves.

The reduction of plant nutrient concentration with plant age has been extensively researched for N (Le Bot *et al.*, 2001; Lemaire *et al.*, 2008) and has been described as the “N dilution curve”, namely a negative power function of N concentration (%) against plant dry matter (DM, tonne ha⁻¹):

TABLE 4
Critical nutrient concentration in tomato leaves at different developmental stage (5-leaf stage, flower initiation and onset of fruit formation)*

Nutrient	Critical nutrient concentration (% DW)		
	5-leaf	Flower initiation	Fruit formation
N	4.0	3.5	2.5
P	1.0	1.0	4.0
K	6.5	7.0	4.0–4.5
Ca	3.5	3.5	1.8–2.0
Mg	1.6–2.0	2.0	1.0

* Sample consisted of all healthy leaves on the plants, which were grown in a peat-based medium.
Bryson and Barker, 2002

$$\%N = \alpha DM^{-\beta}$$

Eq. 1

where:
coefficient α represents plant N percent concentration when crop DM is 1 tonne ha⁻¹
 β represents the coefficient of dilution which describes the relationship of decreasing N concentration with increasing shoot biomass

Equation 1 is valid for plants grown under non-limiting N supply.

The concept of the N dilution curve accounts for the progressive decline of N uptake with crop growth. The following relationship between crop N uptake (NU) and DM production (with both quantities expressed in kg ha⁻¹) was derived by Gallardo *et al.* (2009) from a greenhouse tomato spring crop:

$$NU = 0.0699DM^{0.9016}$$

Eq. 2

To conclude, knowledge of the crop growth rate and critical nutrient concentration of plant tissues is crucial for efficient fertilization management. Crop modelling can be an excellent tool for predicting the actual mineral uptake of greenhouse plants based on environmental and growing conditions. However, crop models are not available for all greenhouse crops and, more importantly, their application on a commercial scale is not straightforward, especially in the low-tech greenhouse operations typical of Mediterranean regions.

MINERAL NUTRITION, PLANT HEALTH AND PRODUCE QUALITY

Nutrients and plant health

As previously reported, too low or too high supply of a nutrient may result in deficiency or toxicity, with nutrient deficiencies more frequent than toxicities in commercial greenhouse crops. Sometimes, a too high supply of a nutrient can cause deficiency of another nutrient (rather than direct toxicity of the nutrient in excess) as a result of competitive restriction of its uptake.

The visual diagnosis of nutrient deficiencies is not always easy since different nutrients can cause similar symptoms, while in some cases two or more nutrient deficiencies may coexist in the same plant. Nevertheless, a preliminary screening may be based on the physiological age of the leaves in which the symptoms first appear (Table 5). As a rule, nutrients that are highly mobile through the phloem may be remobilized from older leaves and retranslocated to young growing organs, should supply shortages occur. Hence, the symptoms of deficiency in these nutrients

TABLE 5
Physiological age of leaves in which early deficiency symptoms appear, based on the mobility of plant nutrients through the phloem

Old leaves	N, P, K, Mg
Intermediate to young leaves	Mn, Mo
Young leaves	Ca, S, Fe, Zn, Cu,
Shoot apices	B

appear first in the older leaves. In contrast, nutrients with poor mobility through the phloem cannot be retranslocated from old to young leaves when their availability decreases. Deficiency symptoms for these nutrients therefore appear first in new vegetation in the upper plant.

Nutrient imbalances can also interfere with physiological disorders. Most physiological disorders result from multiple factors related not only to plant nutrition but also to irrigation and environmental conditions; many affect the fruit and are detrimental to both marketable yield and fruit quality.

Physiological disorders

Physiological disorders in fruit can have a strong impact on the economic return of the greenhouse enterprises. A typical physiological disorder related to plant nutrition is blossom end rot (BER), affecting Solanaceae fruit crops (tomato, pepper and eggplant). Blossom end rot usually begins as a small water-soaked area at the blossom end of the fruit and then develops into a dry rot. This disorder is ascribed to a local shortage of Ca in the distal part of the fruit, resulting in tissue disorganization due to impairment of plasma membranes or cell walls. Environmental conditions (e.g. low relative humidity in the air, high air temperature and solar radiation intensity) and fertilization and irrigation management may restrict the translocation of Ca to the affected part of the fruit. In most cases, the fruit Ca level correlates poorly with the appearance of BER – presumably because the fruit cell damage caused by Ca shortage occurs during a period of rapid cell elongation, while the visible symptoms do not appear until later, when the Ca supply has recovered.

While eggplant is less susceptible to BER than tomato or pepper, some cultivars may be affected by another disorder caused by local shortage of Ca in the fruit: internal fruit rot (Savvas and Lenz, 1994). It first appears as an uneven, wet area in part of the external fruit surface; below this uneven area, the fruit tissue has a wet, blackened and disintegrated appearance, resulting from the bursting and disorganization of cells. At a later stage, the skin may crack, followed by excretion of a black juice.

Another physiological disorder related to plant nutrition is the occurrence of colour spots or flecks in tomato and pepper fruit. Tomato is mainly affected by gold specks, caused by an excess of Ca deposition in the cell walls. Undesired colour spots or flecks may also appear in pepper as a result of inappropriate plant nutrition. The occurrence of colour spots in pepper can be reduced by applying high rates of nitrogen fertilization and by shading the crop to reduce solar radiation intensity. In soilless culture, the incidence of white flecks and green spots may be reduced by increasing the strength of the nutrient solution (higher electrical conductivity).

Blotchy ripening occurs in tomato fruit and it is associated with nutrition. While most of the fruit surface turns red on ripening, some patches remain strikingly green, grey or yellow. When grey patches are prevalent, the disorder may also be known as “grey wall”. Blotchy ripening is more likely to occur when there are relatively low nutrient concentrations in the root zone; an inverse relationship between the percentage of unevenly ripened fruits and the levels of K and N in the root zone of tomato has been reported (Adams *et al.*, 1978).

Yellow shoulder disorder (YSD) is a ripening disorder of tomato. It is characterized by discoloration of the proximal-end tissues of the fruit, which remain yellow or green, while the rest of the fruit surface turns red. YSD incidence would appear to be influenced by K, N and P supply. Enhanced (though not excessive) fertilization with K improves fruit colour in tomato, while at the same time it reduces the incidence of yellow shoulder and other fruit colour disorders.

Fruit cracking in tomato and pepper depends on plant nutrition. It occurs when the internal fruit expands more rapidly than the epidermis, causing the latter to split. Incidence of fruit cracking can be decreased by reinforcing the cell walls and membranes. Certain types of cracking are considered Ca-related disorders. Mineral deficiency or excess can increase the crop’s susceptibility to physiological disorders and diseases during storage. Excess nitrogen increases the incidence of bacterial (*Erwinia carotovora*) soft rot and internal browning in tomatoes and aggravates the severity of stem cracking (or brown checking) in celery, associated with B deficiency (Bartz *et al.*, 1979).

BOX 6

How to restrict the occurrence of blossom end rot (BER) in Solanaceae fruits

- Use non-susceptible cultivars to BER.
- Take measures to maintain the relative humidity levels > 60% in the greenhouse air during the hot season of the year to avoid excessive transpiration rate.
- Avoid too high air temperatures inside the greenhouse during the hot season of the year.
- Avoid excessive K or Mg supply via fertilization.
- Supply only part of nitrogen in the form of $\text{NH}_4\text{-N}$, because $\text{NH}_4\text{-N}$ aggravates the incidence of BER.
- Avoid high salinity levels in the root zone.
- During the winter, maintain a root temperature of 18-20 °C at night.
- Ensure that the soil Ca level is adequate, especially if plants are grown in a sandy or acidic soil, or the SOM is very high.
- If the above measures are not effective enough, spray the very young fruit with a 0.5% solution of calcium chloride.
- Remove consistently all plant leaves below the clusters to be harvested, especially under warm weather conditions.

Nutrients and quality of produce

Produce quality may be defined as the degree to which a series of extrinsic or intrinsic characteristics of a given product fulfil the requirements expressed by the consumers: quality represents the conformance to preset specifications (standards). In recent years, in developed countries, the idea of quality for fresh vegetables has changed significantly, depending on numerous factors and incorporating social and cultural connotations. Fresh vegetables are commonly selected by consumers on the basis of their appearance and price; but repeated purchase depends not so much on price as on other attributes (e.g. organoleptic and nutritional value) – at least on some markets. Consumers also expect produce to be free of pesticide residues. The organoleptic quality of fresh products is generally attributed to their colour, flavour, and content of sugar, acids and volatiles; freshness in leafy vegetables and firmness and juiciness in fruits are also important.

Interest in the nutritional and health benefits of fresh vegetables has grown in recent years. In general, vegetables contain biologically active substances, as well as nutrients, including pro-vitamin A, vitamin C, calcium, iron, folate, potassium, magnesium, digestible and non-digestible (fibre) carbohydrates, proteins and secondary metabolites (flavonoids and carotenoids, mainly); they lack saturated fat and trans fatty acids, and contain a low amount of Na (with some exceptions).

Fruits and vegetables are important components of a healthy diet, and adequate daily consumption can prevent a whole range of diseases and disorders, including cancer, cardiovascular diseases, neurodegenerative diseases and metabolic diseases. Year-round availability, post-harvest shelf-life, adequate packaging and special presentations (e.g. ready-to-eat products) are all important quality criteria for fresh vegetables. Moreover, consumers increasingly wish to know how and where products were cultivated and more environment-friendly cropping systems are expected. The greater the number of attributes and benefits demanded by consumers, the more fresh vegetables cease to be commodities and become specialties; their added value and price naturally increase as a result.

Certification of product quality, provided by big retail companies (super- and hypermarkets) or by independent entities on the basis of regulations promulgated by national or transnational (e.g. European Union) governments, is now applied to most greenhouse fresh vegetables. Growers are motivated to improve their growing techniques and to apply quality management systems in all phases of production, including post-harvest handling and storage. Fertilization is a potential tool not only to control crop yield, but also to improve quality and sensorial aspects while respecting the environment.

The case studies that follow aim to illustrate how appropriate management of mineral nutrition, including the application of specific fertilizers, may improve product quality and facilitate its marketability.

Controlling nitrate accumulation in vegetables

Nitrate is a natural substance that *per se* is not toxic to humans; however, it may lead to the formation of nitrite, nitric oxide and N-nitrous compounds, with potential health effects, including methaemoglobinaemia and carcinogenesis. A dose of 222 mg per day for a 60 kg adult was recognized as the Acceptable Daily Intake (ADI) of nitrate by the FAO/WHO Expert Committee on Food Additives in 2002. In humans, nitrate intake is mainly associated with the consumption of vegetables and, to a lesser extent, of water and other foods and beverages (e.g. beer).

In plants, high levels of nitrate can be found in leaves, while much lower levels occur in fruits, seeds or root organs. Herbs (e.g. basil and coriander), leafy vegetables (e.g. lettuce, spinach and rocket) and stems (e.g. celery) have a good capacity for accumulating large amounts of nitrate in their leaves (up to 15–20 g kg⁻¹ FW); on the other hand, a much lower content is generally found in brassicas, fruit vegetables (with the exception of zucchini and pumpkin), legumes, tubers, bulbs and mushrooms (EFSA, 2008; Table 6).

High vitamin-C content – typical of many vegetables – may prevent the conversion of nitrate to nitrite in plant tissue and within the human body, thus further reducing the risk of nitrate toxicity. Moreover, it has been found that nitrate metabolites (e.g. nitric oxide) have important physiological roles (e.g. vasoregulation) (Lundberg *et al.*, 2006; Webb *et al.*, 2008).

The EU has set certain limits for the nitrate content of vegetables for fresh consumption or processing, for example, for baby food production (EC Regulation No. 1881/2006). Limits on the nitrate content of other vegetables,

TABLE 6
Classification of vegetables according to the typical nitrate content (mg kg⁻¹ FW)

Very low (< 200)	Low (200–500)	Middle (500–1 000)	High (1 000–2 500)	Very high (> 2 500)
Artichoke	Broccoli	Cabbage	Celeriac	Celery
Asparagus	Carrot	'Cima di rapa'	Chinese cabbage	Chervil
Broad bean	Cauliflower	(broccoli raab)	Endive	Cress
Brussels sprouts	Cucumber	Dill	Escarole	Lamb's lettuce
Eggplant	Pumpkin	'Radicchio'	Fennel	Lettuce
Garlic	'Puntarelle' chicory	Savoy cabbage	Leaf chicory	Red beetroot
Green bean		Turnip	Leek	Rocket
Melon			Parsley	Spinach
Mushroom			Kohlrabi	Radish
Onion				Swiss chard
Pea				
Pepper				
Potato				
Summer squash				
Sweet potato				
Tomato				
Watermelon				

including potato (considering the large daily consumption of this foodstuff), have been established in some European countries. On the other hand, no nitrate standards have been introduced in the United States (Santamaria, 2006).

Excessive nitrate accumulation in plant tissues occurs when there is an imbalance between root uptake and nitrate assimilation in the leaves. Growing conditions reducing the rate of photosynthesis while root uptake of nitrate remains relatively high inevitably results in nitrate accumulation, especially in the leaves (even more in their petioles), following the transportation of nitrate through the transpiration stream. Indeed, nitrate tends to accumulate in transpiring organs (e.g. leaves), while fruits, seeds and storage organs (tubers and bulbs) have relatively small concentrations. Leaf nitrate content is generally higher early in the morning than in the afternoon, due to the lower availability of photosynthetic products (sugars, assimilatory power) that slow down the nitrate transformation.

Low radiation is the main factor responsible for excessive nitrate accumulation. Nitrate levels in plant tissues therefore tend to be higher in northern countries, in winter and under cover in comparison to southern countries, in summer and field cultivation (EFSA, 2008). Intriguingly, the EU limits on nitrate content in vegetables depend on the season and growing system – it would seem that agronomic considerations outweigh any health concern (Table 7).

BOX 7

Measures for reducing nitrate accumulation in leafy vegetables

Soil and soilless culture

- Select cultivars known for lower nitrate accumulation.
- Increase light transmission of greenhouse cover.
- Remove outer leaves from head vegetable.
- Split nitrogen top-dressing.
- Do not apply N fertilization shortly before harvest.
- Check nitrate concentration in leaf or petiole sap with quick nitrate test.

Soil culture

- Use ammonium instead of nitrate.
- Check soil nitrate level.
- Harvest crop in the afternoon.
- Split nitrogen top-dressing and suspend it well before harvest.

Soilless culture

- Remove nitrate from nutrient solution a few days before harvest.
- Replace part of nitrate with chloride.

TABLE 7

Maximum levels (limits) for the nitrate (mg kg⁻¹ fresh matter) in lettuce and spinach according to European Commission Regulation (EC) No. 563/2002²

Product	Harvest period	NO ₃
Fresh spinach ^a (<i>Spinacia oleracea</i> L.)	Harvested 1 Nov. – 31 Mar.	3 000
	Harvested 1 April – 31 Oct.	2 500
Preserved, deep-frozen or frozen spinach		2 000
Fresh lettuce (<i>Lactuca sativa</i> L.) (protected and open-grown lettuce) excluding 'Iceberg' type	Harvested 1 Oct. – 31 Mar.	
	- grown under cover	4 500
	- grown in the open air	4 000
	Harvested 1 April – 30 Sept.	
'Iceberg' type lettuce	- grown under cover	3 500
	- grown in the open air	2 500
	- grown under cover	2 500
	- grown in the open air	2 000

^a The maximum levels for fresh spinach do not apply to fresh spinach which is subject to processing and directly transported in bulk from field to processing plant.

Biofortification of vegetables

Humans need many mineral elements and they are supplied by food. In some regions, however, populations are at risk of deficiency of certain minerals, for example Fe, Zn, Ca, Mg, Cu, iodine (I) and selenium (Se), due to limited dietary variety or poor levels of these elements in their food. Conventional strategies to solve mineral deficiencies are direct supplementation or food fortification. Biofortification represents an alternative strategy: the increase of the bio-available concentrations of an element in food crops by means of fertilization and plant breeding (either conventional or based on recombinant DNA technology) (White and Broadley, 2005; Ríos *et al.*, 2008; Voogt *et al.*, 2010). However, biofortification of greenhouse vegetables seems to be more of a marketing than a health policy tool, as greenhouse products are principally sold in developed countries where populations have good access to many micronutrient-rich (e.g. meat, fish, poultry and dairy products) or fortified (e.g. table salt) foods and therefore are at low risk of micronutrient malnutrition.

In Italy, a few field-grown vegetables (potatoes and onions) enriched with Se or I (by foliar application or fertigation) have been successfully launched on the market. Nevertheless, the real advantages of consuming these products still need to be assessed; there is concern about consumption by people not at risk of malnutrition and therefore having a potential overintake of micronutrients.

From a technical point of view, micronutrient biofortification is achieved through foliar or soil application (preplanting, top-dressing or fertigation) of specific salts (e.g. potassium selenate or selenite, potassium iodine or iodate) or fertilizers enriched with the element of interest. Hydroponic culture simplifies vegetable biofortification, as the micronutrient can be dissolved directly in the nutrient solution. This cultural method generally facilitates plant mineral uptake and increases the efficiency of micronutrient application. Micronutrient supplements can positively influence plant growth (most of them are essential

plant elements) and improve product quality. For example, the application of Se can enhance the shelf-life of fresh-cut leafy vegetables, because it interferes with ethylene synthesis.

Some authors have proposed hydroponic cultivation of metal-accumulating species (e.g. *Brassica juncea*) in order to grow dried plant products containing multiple minerals (Fe, Zn, Mn, Cu, Cr, Se, V and Mo) as dietary supplements. Hydroponics has also been used to enrich vegetables with nutritional factors such as Ω -3-fatty acid. All programmes for micronutrient enrichment of greenhouse vegetables must be supported by comprehensive risk-benefit analysis followed by appropriate communication to consumers, assessing, for example: risks of overdose; negative health effects; possible micronutrient accumulation in the soil; and leaching to ground- or surface water.

Quality of hydroponically grown vegetables

Literature provides contrasting evidence; nevertheless, hydroponics generally enables the production of vegetables of quality comparable to those grown in soil (Gruda, 2009). Some species, such as tomato, cucumber, pepper, strawberry and almost all leafy plants (lettuce, rocket salad, basil, celery), seem to respond better to hydroponic culture than other crops, such as eggplant and muskmelon. For example, reduced sweetness and firmness of hydroponically grown muskmelons is often observed (Pardossi *et al.*, 2000). Moreover, leafy and fruit vegetables produced hydroponically do not contain the residues of chemicals used for soil disinfection or other soil pollutants and, usually, they are very clean – a crucial factor for strawberry and ready-to-eat leaf and shoot vegetables (microgreens, baby leaves), the consumption of which is rapidly increasing in many countries. Cultivation of strawberries in suspended bag culture reduces labour costs for planting and harvesting, and significantly reduces susceptibility to grey mould (*Botrytis cinerea*). Proper manipulation of the culture solution can substantially improve nutritional or sanitary characteristics – for example, to reduce the level of nitrates.

NUTRIENT MANAGEMENT TO MAXIMIZE YIELD AND MINIMIZE NUTRIENT LOSS

Fertilization accounts for a relatively small proportion of total production costs of greenhouse crops (< 5–10%); what is more, there is a general (partial) misconception that abundant nutrient application is needed for high yield and quality. As a result, growers tend to overfertilize. Crop production is not linearly related to the level of fertilization: with knowledge of the crop nutrient requirements as a whole and of how the mineral uptake rate and mutual ratio change during the growing season it is possible to optimize mineral supply and maximize crop growth, reduce the amount (and cost) of applied fertilizers, and minimize the amount of unused nutrients destined to accumulate in the soil and be emitted in the ground- and surface water.

Mineral fertilizers

A fertilizer is a mined, refined or manufactured product containing one or more essential plant nutrients in available or potentially available forms and in commercially valuable amounts without carrying any harmful substance above permissible limits (FAO, 2006). Prefixes (synthetic, mineral, inorganic, artificial, chemical etc.) are often used interchangeably to describe fertilizers. Although organic fertilizers are being prepared and used, the term “fertilizer” does not actually include them, for reasons of tradition and because of their generally much lower nutrient content (FAO, 2006). Fertilizers are traditionally classified as follows:

- Single-nutrient or straight fertilizers containing one of the three major nutrients (N, P, K). They often include secondary nutrients (e.g. elemental S, magnesium sulphate, calcium oxide).
- Complex or compound fertilizers containing at least two of the three major nutrients. They are produced by a chemical reaction between the raw materials containing the desired nutrients and are generally solid granulated products. They include both two-nutrient (NP) and three-nutrient (NPK) fertilizers.

The available plant nutrients in fertilizers (fertilizer grade) are expressed as a percentage by weight in a fertilizer. For example, a 12–32–16 grade of NPK complex fertilizer indicates the presence of 12% nitrogen (N), 32% phosphorus pentoxide (P_2O_5) and 16% potash (K_2O). On a fertilizer bag, the NPK content is always written in the sequence: N, P_2O_5 , K_2O . There are a wide variety of N, P and K fertilizers that can be applied in greenhouses through fertilization and fertigation (Table 8). The choice of fertilizer used for fertigation is mainly based on solubility and on residual contents of salts (not usually harmful to the plants but can cause clogging of drippers).

TABLE 8
N, P and K fertilizers most used in greenhouse production

N fertilizers	Chemical formula	P fertilizers	Chemical formula	K fertilizers	Chemical formula
Ammonium nitrate	NH_4NO_3	Super phosphate	$Ca(H_2PO_4)_2$	Potassium sulphate	K_2SO_4
Nitrochalk	$NH_4NO_3 + CaCO_3$	Monopotassium phosphate	KH_2PO_4	Potassium magnesium sulphate	$K_2SO_4 \cdot MgSO_4$
Ammonium nitrate solution	NH_4NO_3	Mono-ammonium phosphate	$NH_4H_2PO_4$	Potassium nitrate	KNO_3
Ammonium sulphate	$(NH_4)_2SO_4$	Phosphoric acid	H_3PO_4	Potassium chloride	KCl
Calcium nitrate	$5[Ca(NO_3)_2 \cdot 2H_2O] \cdot NH_4NO_3$	Dicalcium phosphate	$CaHPO_4$	Potassium hydroxide	KOH
Calcium nitrate solution	$Ca(NO_3)_2$	Polyphosphate	-	Potassium bicarbonate	$KHCO_3$
Urea	$CO(NH_2)_2$			Potassium carbonate	K_2CO_3
Nitric acid	HNO_3				

- **N fertilizers.** The most commonly used contain N as NO_3 , NH_4 or urea; generally, urea is not used for soilless production.
- **P fertilizers.** Orthophosphates are usually applied. Calcium orthophosphates are the cheapest and most widely used on soil-grown crops, but they are never used in fertigation or soilless production as they include many insoluble components. Moreover, many P fertilizers contain fluorine (F), which is toxic for some crops, especially bulbous and tubercles; for such crops, P fertilizers with a low F content are found on the market.
- **K fertilizers.** The most widely used are K sulphates. Potassium chloride (KCl) is never applied on greenhouse soil-grown crops, but in soilless crops it may be used when Cl is required in the nutrient solution and the concentration in the irrigation water is very low.

Kieserite is the most common contributor of Mg to crops, although it is not very soluble in cold water. For fertigation and soilless systems, Epsom salt is preferred. Many Ca fertilizers have a double function, because they are also used as pH regulators, for example CaCO_3 and Ca(OH)_2 . However, when only Ca supply is required, $\text{Ca(NO}_3)_2$ is normally applied. Micronutrient availability depends on several factors, including the pH of the soil and nutrient solution. Many are applied as sulphates (SO_4); chlorides (Cl) and nitrates (NO_3) are also used.

Iron is applied through chelates, which are soluble and help keep Fe in the solution for uptake (Box 8). The uptake of the whole chelate molecule is low and Fe is usually removed from the chelate prior to uptake. Chelates most widely used in agriculture are EDTA (ethylene diamine tetraacetic acid), DTPA (diethylene triamine pentaacetic acid) and EDDHA (ethylene diamine di-o-hydroxyphenylacetic acid). Other chelate compounds are HEDTA (hydroxyethyl ethylene diamine triacetic acid) amino acids, humic-fluivic acids and citrate. The choice of iron chelate depends on the pH of nutrient solution and growing media that affects the stability of chelates and the availability of Fe.

TABLE 9

Secondary fertilizers and micronutrients most used in greenhouse production

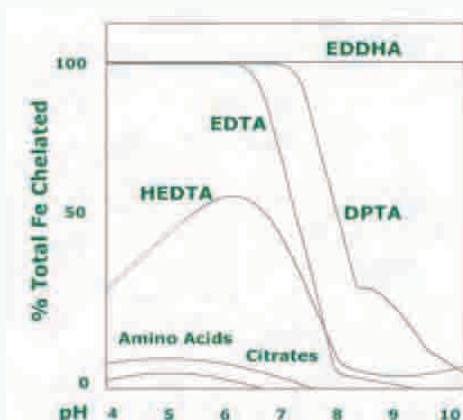
Mg fertilizers	Chemical formula	Ca fertilizers	Chemical formula	Micronutrients	Chemical formula
Kieserite	$\text{MgSO}_4 \cdot \text{H}_2\text{O}$	Slaked lime	Ca(OH)_2	Manganese sulphate	$\text{MnSO}_4 \cdot \text{H}_2\text{O}$
Epsom salt	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	Limestone	$\text{CaCO}_3 + \text{MgCO}_3$	Zinc sulphate	$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$
Magnesium nitrate	$\text{Mg(NO}_3)_2 \cdot 6\text{H}_2\text{O}$	Calcium chloride	$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	Bórax	$\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$
Magnesium nitrate solution	$\text{Mg(NO}_3)_2$	Calcium nitrate solution	$\text{Ca(NO}_3)_2$	Boric acid	H_3BO_3
				Cooper sulphate	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
				Sodium molybdate	$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$
				Iron chelate	Fe-EDTA/ Fe-DTPA/ Fe-EDDHA

BOX 8

What are iron chelates

Chelates are compounds that stabilize Fe^{3+} ion and other positively charged metal ions (Zn^{+2} , Mn^{+2} and Cu^{+2}) and protect them from oxidation and precipitation.

Different chelates hold Fe ions in different strengths at different pH levels. They also defer in their susceptibility to Fe replacement by competitive ions. For example, at high concentrations, Ca or Mg ions may replace the chelated metal ion.



- Fe-EDTA is stable at pH below 6.0. Above pH of 6.5, nearly 50% of the Fe is unavailable. Therefore, this chelate is ineffective in alkaline soils. This chelate also has high affinity to Ca, so it is advised not to use it in Ca-rich soils or water.
- Fe-DTPA is stable in pH levels of up to 7.0, and is not as susceptible to iron replacement by calcium.
- Fe-EDDHA is stable at pH levels as high as 11.0, but it is also the most expensive iron chelate available.

In soilless media and hydroponics, pH monitoring and control of water and media is easier than in soils. When regular testing is performed, and pH control is adequate, it is possible to prefer the inexpensive, less stable Fe chelates.

The fertilizer industry also produces compound fertilizers. Normally, these fertilizers are composed of N, P and K in varying ratios. The newest products also include secondary cells as Mg and micronutrients. They are widely used, especially in open field crops, but problems may arise from their application:

- Many N-P-K compound fertilizers include large amounts of sulphates (SO_4).
- They generally contain unnecessarily high quantities of P.
- Their fixed composition frequently does not match with the nutrients already available and consequently with the crop requirement for N, P and K. Indeed, in greenhouse production it is advisable to apply simple N, P and K fertilizers to optimize nutrient management.

Other forms of fertilizer available are controlled- or slow-release fertilizers, coated in a substance to enable a slow rate of release. There are four main categories:

- Plastic-coated fertilizers (e.g. Osmocote) are spheres coated with plastic and containing water-soluble fertilizer. The spheres are generally 3 mm

in diameter and the thickness of the coating determines the release time. Once applied to the soil, water penetrates the coating and enters the sphere; pressure builds up, causing cracks to form, through which the fertilizer passes into the soil.

- Slowly soluble coated fertilizers have limited solubility. The most common is MagAmp (7-40-6, N-P-K formulation). This kind of fertilizer may reduce the availability of Fe, Mn, Cu and Zn due to the high level of phosphate. Ammonium toxicity may also be a problem with a low pH.
- Urea aldehydes contain high levels of N. The most common type is urea formaldehyde. These fertilizers are mineralized by micro-organisms that break them down releasing N plant uptake.
- Sulphur-coated fertilizers include many fertilizer types that are coated separately with sulphur and a sealant, then mixed together. The fertilizer is released by soil micro-organisms.

In greenhouses these types of fertilizer are not usually used since slow fertilizer release frequently does not match the crop nutrient uptake rate. Moreover, nutrient release from fertilizers is out of control as it depends on many factors (e.g. temperature and soil moisture, activity of soil micro-organisms).

Organic manures and fertilizers

Organic manures and fertilizers are derived principally from substances of plant and animal origin. These sources cover manures made from cattle dung, excreta of other animals, other animal wastes, rural and urban wastes, composts, crop residues and green manures.

The term organic manure is used collectively for cattle dung, FYM (farmyard manure), composts etc., all of which have a large volume in relation to the nutrients contained in them. Organic manures act primarily on the physical and biophysical components of soil fertility. They are normally applied to increase the level of organic matter and the abundance of micro-organisms in the soil, thus improving soil biodiversity and the physical properties of the soil. Improvement in soil aggregation with the application of organic manure results in increased porosity, hydraulic conductivity, infiltration rate, and water-holding capacity, and decreased bulk density and penetration resistance. Indeed, they are also referred to as “soil improvers” (FAO, 1998).

Determining the correct amount of manure to apply is difficult. Manure samples should be analysed for nutrient content and levels of metals (e.g. Cu) often present in poultry litter. Nitrogen available to the plant is lower than the content in the samples: loss occurs through volatilization with spreading, and only part of the organic N becomes available to plants through mineralization during the growing season.



Plate 3
Application of organic soil improver in greenhouse

“Organic fertilizer” refers to concentrated organic manures (e.g. oilcakes, slaughterhouse waste, guano) and they must normally contain a minimum 5 percent of nutrients ($N + P_2O_5 + K_2O$) (FAO, 2006). The raw materials used for organic fertilizer preparation are processed by drying, shredding, mixing, granulating, odour removal, pH modification, partial fermentation and composting, and always with proper hygienic control (FAO, 2006). This process provides standard products with certified concentrations of organic matter, a definite C:N ratio, guaranteed nutrient concentrations, and products without growth-impeding substances or sanitary problems (FAO, 2006). Finally, they are also easy to store and handle. Organic fertilizers are used where low nutrient concentrations and slow-acting N sources are preferred. Some of these are important inputs in organic farming. Commercial organic fertilizers are classified as follows (FAO, 2006):

- Organic N fertilizers ($\geq 5\%$ N, often higher)
- Organic P fertilizers, mainly from bones (e.g. $25\% P_2O_5$)
- Organic NP fertilizers ($\geq 3\%$ N and $12\% P_2O_5$)
- Organic NPK fertilizers ($\geq 15\%$ N, P_2O_5 and K_2O)
- Organomineral NP or NPK fertilizers, supplemented by mineral fertilizer or guano (e.g. NP with $\geq 5\%$ each of N and P_2O_5 , or NPK with $\geq 4\%$ each of N, P_2O_5 and K_2O)
- Organomineral fertilizers based on peat, but with nutrient supplements.

The most generally used organic fertilizers and soil improvers in greenhouse crops (Table 10) are similar to those habitually applied in open field cultivation (Elherradi *et al.*, 2005; Thompson *et al.*, 2007).

TABLE 10
Composition of some generally organic sources applied in greenhouse production

Material	Nutrient content (%)		
	N	P_2O_5	K_2O
<i>Organic fertilizer</i>			
Blood meal	10–12	1–2	0.5
Feather meal	13	0	0.5
Bone meal	5	16	–
Chicken pellets	2.2	0.8	1.2
Cow pellets	1.9	1	2.7
Guano	0.4–9	12–26	–
<i>Organic manures and compost</i>			
Farmland manure	0.5	0.15	0.5
Poultry manure	2.87	2.9	2.35
Rural waste compost	0.5	0.2	0.5
Urban waste compost	1.5	1.0	1.5

Assessment of crop nutrient requirements based on soil and plant nutrient status

Soil nutrient status is used to more accurately design crop fertilization schemes before crop establishment; in most cases, soil nutrient status is a standard data component in planning crop fertilization.

The assessment of the plant nutrient status, especially in greenhouses, is used as a diagnostic tool to identify possible nutrient deficiencies or toxicities during cropping. Plant tissue analyses for screening the plant nutrient status are usually conducted when plants exhibit visible signs of nutrient disturbances or poor growth, although in some cases they may be used preventively as a monitoring tool to guide fertilization.

Sampling and analysis of soil nutrients

The classic approach for estimating plant nutrient availability in the soil is the determination of exchangeable nutrient cations, based on the use of acetic acid and DTPA solutions for the extraction of plant available macro- and microcations, respectively. The target level for some cations (e.g. K) may vary in relation to soil texture (Table 12). However, the determination of exchangeable cations is laborious and time-consuming, since it requires the drying of soil samples. Furthermore, this method is restricted only to cations, while the determination of essential nutrients occurring as anions (P, N) or uncharged compounds (B) requires other procedures, for example the Olsen method, which is routinely used to estimate the plant available P in Mediterranean soils (Olsen and Sommers, 1982).

Using the bulk density of the soil, it is possible to convert all soil nutrient concentrations into kg ha⁻¹ – a sound basis for estimating fertilizer application dosages. However, to convert soil nutrient concentrations into kg per cultivated greenhouse area, it is necessary to define the soil depth utilized by plant roots for nutrient acquisition. In long-term greenhouse crops, such as tomato, a soil depth of 60 cm is used as a basis for calculating the available nutrient reserves in the soil. However, nutrient concentrations change with increasing soil depth; therefore, for an accurate calculation of the soil nutrient status, soil samples from different

TABLE 11
Desired levels of exchangeable cations, plant available P (Olsen) and B (hot water extraction) in greenhouse soils based on experience and standard laboratory practices (mg kg⁻¹ dried soil)

Nutrient	Desired range	Nutrient	Desired range
Ca	1 200–5 000	Fe	5–150
Mg	60–350	Mn	2–80
K	120–500	Zn	0.7–2
Na	>500	Cu	0.5–2
P	10–40	B	0.3–1.5

TABLE 12
Interpretation of soil test values for exchangeable K in relation to soil texture

Rating	Exchangeable K (mg kg ⁻¹ soil)		
	Sandy soils (1,2,4) ^a	Loamy soils (5,6,7,8)	Clay and silty soils (3,9,10,11,12)
Very low	<40	<60	<80
Low	40–80	60–100	80–120
Medium	81–120	101–150	121–180
High	>120	>150	>180

^a Soil texture classification (see Box 1).
CRPV, 2010

depths are taken. In most cases, soil samples from 0–30 and 30–60 cm soil layers are taken, but the collection of samples from shallower soil layers (0–20, 20–40 and 40–60 cm) is also possible. In greenhouse-grown plants developing a flat-root system, such as lettuce, soil sampling at a depth of 0–30 or 0–40 cm is sufficient to estimate the amounts of available nutrients in the soil.

Determination of plant nutrient status

The first level in assessing the plant nutrient status is based on visual observation of the plant. Although visual estimation is a subjective means of diagnosing the plant nutrient status, it is very important, first because it is the cheapest and most rapid, and second because it enables a first screening. Nevertheless, in many cases, an estimation of the plant nutrient status by means of chemical analysis may be needed, either to confirm suspected nutritional disorders, or to exclude them if the symptoms do not point to a typical nutrient deficiency or toxicity.

To assess the nutrient status in greenhouse plants, leaf samples are collected from representative plants and subjected to chemical analysis in a laboratory. The physiological age of the leaves used for the analysis is extremely important, because the levels of most nutrients exhibit a concentration gradient with increasing leaf age. The results obtained from the chemical analysis are compared with optimal concentration ranges suggested in various literature sources (Hanan 1998; Mills and Jones, 1996), which are specific for each nutrient and cultivated plant species. However, the establishment of an optimal concentration range for a particular nutrient is based on a series of measurements in leaves of a well-defined physiological age (e.g. fifth leaf from the top of the stem, or the leaf above or below the youngest fruit). Therefore, when optimal concentration ranges are given for the leaves of cultivated plants aiming to diagnose nutritional disorders, these are always accompanied by a description of the physiological age of the leaves to be sampled. In most cases, the recommendation for greenhouse vegetables is to sample and analyse the youngest fully grown leaves (Tables 13 and 14).

Sampled leaves should be washed carefully with distilled water to remove dust or other compounds on the leaf surface. The leaf samples are then oven-dried at 65–105 °C to reach a constant weight. A temperature of 65–70 °C is commonly used to determine the leaf N concentration, because at higher temperatures some N may escape in the form of volatile N compounds. Higher temperature levels (up to 105 °C) are permissible only when samples are used exclusively to determine metallic macronutrient concentrations. The dried leaves are powdered and passed through a 40-mesh sieve (0.42-mm openings). To determine the concentrations of K, Ca, Mg, P, Fe, Mn, Zn, Cu and B in the leaf tissues, a specific quantity (500 mg) of the powdered leaf sample is weighed and subjected to dry ashing in a muffle furnace at 550 °C for 5 hours. The nutrients are extracted from the leaf ash using a HCl solution at a concentration of 1 M – a procedure known as dry ashing. These nutrients can also

TABLE 13

Optimal range of leaf macronutrient concentrations for common greenhouse crops in Mediterranean countries

Plant species	Macronutrient (% in dry weight)					Sampled plant part
	N	P	K	Ca	Mg	
Tomato	3.0–5.0	0.20–0.60	3.5–6.0	2.0–4.0	0.35–0.80	Most recent fully expanded leaf
Pepper	3.0–4.5	0.30–0.60	3.0–7.5	1.0–2.5	0.35–0.90	Most recent fully expanded leaf
Eggplant	4.0–5.5	0.30–0.60	4.0–6.5	1.0–2.2	0.30–1.00	Most recent fully expanded leaf
Cucumber	4.5–6.0	0.30–0.80	2.5–5.5	3.0–6.0	0.50–1.20	Fifth leaf from the apex
Zucchini	4.0–6.0	0.30–0.50	2.5–5.0	2.0–3.5	0.25–1.00	Fifth leaf from the apex
Melon	4.0–5.5	0.30–0.70	3.5–5.5	2.0–3.5	0.35–0.8	Fifth leaf from the apex
Watermelon	2.0–5.0	0.20–0.60	2.5–4.5	1.5–3.5	0.40–0.80	Fifth leaf from the apex
Bean	3.0–6.0	0.25–0.75	3.0–7.5	0.8–3.0	0.25–0.80	Most recent fully expanded leaf
Lettuce	4.0–5.5	0.30–0.70	5.5–12	0.8–2.5	0.25–0.90	All leaves at head formation
Strawberry	2.1–4.0	0.20–0.45	1.5–2.5	0.6–2.5	0.25–0.70	Young, fully expanded leaves

Krug (1986), Bergmann (1988), Mills and Jones (1996), Hanan (1998), personal experience

TABLE 14

Optimal range of leaf micronutrient concentrations for common greenhouse crops in Mediterranean countries

Plant species	Micronutrient (ppm or mg kg ⁻¹ dry weight)					Sampled plant part
	Fe	Mn	Zn	Cu	B	
Tomato	40–150	30–150	20–80	5–20	30–80	Most recent fully expanded leaf
Pepper	60–300	30–150	20–100	6–25	25–80	Most recent fully expanded leaf
Eggplant	50–300	30–250	20–200	5–15	25–80	Most recent fully expanded leaf
Cucumber	50–300	50–500	25–300	6–18	30–100	Fifth leaf from the apex
Zucchini	50–200	50–250	20–200	10–25	25–75	Fifth leaf from the apex
Melon	50–300	50–250	20–200	7–30	25–60	Fifth leaf from the apex
Watermelon	50–300	40–250	20–250	5–20	25–80	Fifth leaf from the apex
Bean	50–400	30–300	20–200	5–30	25–80	Most recent fully expanded leaf
Lettuce	50–300	30–250	25–250	6–25	25–60	All leaves at head formation
Strawberry	50–250	30–350	20–70	6–20	25–70	Young, fully expanded leaves

Krug (1986), Bergmann (1988), Mills and Jones (1996), Hanan (1998), personal experience

be extracted by applying wet ashing, using a mixture of HNO₃ and HClO₄ as extractants (Kalra, 1998). The concentrations of the above nutrients in the filtered extract are preferably measured by plasma emission spectroscopy (ICP). If an ICP instrument is not available, phosphorus and B are measured colourimetrically, while the metallic nutrient elements are measured by atomic absorption spectrophotometry. The leaf potassium concentration can be accurately measured using flame photometry. The concentration of organically bound N in the leaves is usually measured colourimetrically as NH₄-N after a Kjeldhal digestion (Mills and Jones, 1996). The inorganic fraction of the leaf N (NO₃-N) can also be colourimetrically determined in water extracts. The NO₃- fraction of the leaf N is much smaller than that of the organic N and is not normally measured. Overall, the measurement of the organic leaf N concentration in leaves by means of the Kjeldhal method renders a reliable estimation of the plant N status.

More recent efforts aim to develop rapid, non-invasive methods for determining the plant nutrient status, such as multispectral measurements of colour parameters in leaves and other plant tissues, radiation reflexion, volatile emission etc. Multispectral imaging may be deployed as a means of measuring nutrient status at a canopy level.

Nutrients budget of crops in greenhouse and estimation of optimal fertilizer rate and management

Nitrogen

N fertilization is the most important component of GAP related to plant nutrition, since excessive N supply may raise the nitrate concentrations in edible plant parts and groundwater to harmful levels for human health. Therefore, the N availability in the soil prior to the establishment of the crop is presumably the most important information needed to apply environment- and consumer-friendly fertilization practices in greenhouses. However, the determination of plant-available nitrogen in the soil is not a simple issue, because N in a cultivated field comes from various sources and is removed through loss processes and ultimately with the harvested crop. Such processes can be grouped into two categories (Table 15):

TABLE 15

N budget of the crop: input adds N to the stock of mineral N in the soil; output removes mineral N from the soil

Input of N	Output of N
Initial mineral N at planting ^{*a}	Uptake by the crop ^{*i}
Net mineralization ^{*b}	Denitrification ^{*j}
Atmospheric deposition ^c	Volatilization ^{*j}
N in organic manures (animal manure and compost) ^{*d}	Leaching ^k
N in crop residues ^e	Soil erosion ^c
N in N-fixing legumes included in rotation ^f	Residual mineral N ^{*l}
N with fertilizers ^{*g}	
N in irrigation water ^{*h}	

* Input-output relevant to greenhouse cropping systems.

^a Initial amount of mineral N in the soil at planting; measured by soil analysis.

^b Amount of net mineralization during the growing season, net mineralization being the difference between gross (real) mineralization and immobilization in relation to the C:N ratio of SOM.

^c N added by atmospheric deposition and N lost by soil erosion is negligible in greenhouse.

^d Ammonium and nitrate incorporated, e.g. with manures.

^e Only when the aerial part of previous crop has been incorporated into the soil. Usually it is removed to avoid risk of spreading diseases.

^f Only when legumes such as French beans are grown in greenhouse.

^g Ammonium and nitrate applied as chemical fertilizers.

^h This input of nitrate contained in irrigation water should be taken into account where the amounts are of agronomic significance.

ⁱ Uptake by crop is reported in GAP guidelines.

^j The possibility that denitrification and volatilization occur needs to be minimized.

^k N leaching is negligible in greenhouse if irrigation is managed correctly.

^l The amount of residual mineral N needs to be minimized. Residual N is not directly a loss but in Mediterranean greenhouses it may represent a risk for salinization of the soil.

- Input of N, including the amount of mineral N initially already available and N becoming available as a result of various processes that take place in the soil plus external supply.
- Output of N, including processes and factors that diminish the amount of mineral N in the soil. Mineral N left at harvest is called residual N and is also regarded as an output term.

Proper N management means that numbers need to be assigned to each of the items on the budget, on condition that losses and residual N are minimized, while the utilization of N from all sources is maximized.

Deciding optimal fertilizer rates and times for N dressing is a major challenge in greenhouse horticulture. A common procedure to estimate the N that must be supplied with N fertilization to satisfy the N crop requirement is the N balance sheet method. The N balance sheet is frequently determined as follows (CRPV, 2010):

$$N_f = (Y \times f_N) - (N_p + N_m + N_r + N_s) \quad \text{Eq. 3}$$

where:

N_f = N supplied with fertilization (kg N ha⁻¹)

Y = expected crop yield (tonnes ha⁻¹)

f_N = the amount of N that crop takes up for each tonne of produce (kg N tonne⁻¹ produce)

N_p = N readily available (NO₃⁻-N fraction) in the soil at planting as assessed through soil analysis (kg N ha⁻¹)

N_m = N mineralized from SOM during growing season, estimated by SOM content and C:N ratio, and soil texture (kg N ha⁻¹)

N_r = N mineralized from residues of previous crop, estimated on the basis of origin and management (incorporated into the soil or not) (kg N ha⁻¹)

N_s = N mineralized from organic N sources (manure, compost etc.) distributed in previous years, estimated on the basis of type and amount of organic matter and frequency of its distribution (kg N ha⁻¹)

Estimating the N availability in the greenhouse soil prior to planting is complicated by the difficulty of predicting the mineralization rate of the organic matter during the cropping period. Therefore, if the organic matter content of the soil is not very high, only the inorganic fraction of the soil N, particularly the sum of NO₃⁻-N and NH₄-N, is measured and taken into consideration to estimate the crop needs for N fertilization. This approach is based on the assumption that the organic-N fraction in the soil represents an N-reserve that has to be constantly maintained from year to year, while the contribution of crop residues (e.g. roots) is neglected. However, since the NH₄-N is rapidly converted into NO₃⁻-N in the soil, most laboratories routinely estimate only the NO₃⁻-N fraction in the soil and use this as an estimate of the total plant available nitrogen. If the NO₃⁻-N fraction

TABLE 16

Amount of major nutrients taken up by some crops (kg tonne⁻¹ produce), based on various references

Crop	N		P ₂ O ₅		K ₂ O		RER-GAP ^a			Average ratio N : P : K
	Av.	Range	Av.	Range	Av.	Range	N	P	K	
Basil	3.4	3.0–3.8	1.5	1.3–1.7	4.1	3.2–5.0	3.8	1.3	3.2	2.3:1:2.7
Bean	9.3	1.3–19.0	4.5	2.0–8.0	8.3	6.0–10.0	7.5	2	6	2.1:1:1.9
French bean	6.7	1.3–9.9	2.4	1.0–6.0	7.2	3.3–17.0	7.5	2	6	2.9:1:3.1
Broccoli	8.9	4.0–17.2	2.4	0.6–5.3	8.2	5.0–10.7	5	0.6	6	3.7:1:3.4
Cabbage	3.6	2.5–6.0	1.1	0.3–2.3	3.8	1.6–7.0	4.4	1.8	4.4	3.2:1:3.4
Carrot	3.6	2.4–5.0	1.4	0.4–2.7	5.9	3.2–10.0	4	1.7	6.6	2.6:1:4.3
Cauliflower	4.9	3.3–7.0	2.0	0.7–3.0	6.3	4.0–8.0	4	1.6	5	2.5:1:3.2
Celery	4.9	2.5–8.0	2.4	1.0–4.5	8.4	3.0–12.3	6.5	2.5	10	2.1:1:3.5
Chicory	4.6	3.3–7.0	2.8	1.5–4.5	14.9	4.5–20.0	7	4	20	1.6:1:5.3
Cucumber	2.1	1.5–3.6	1.2	0.1–3.2	3.1	2.0–4.8	1.6	0.8	2.6	1.7:1:2.6
Eggplant	5.0	3.0–7.0	1.5	0.2–2.3	6.2	2.5–11.2	5.4	2.1	6	3.4:1:4.2
Endive	4.9	3.6–6.0	3.2	2.0–4.0	7.1	4.0–9.0	5	3.5	6	1.6:1:2.2
Fennel	4.8	2.3–7.1	1.3	0.9–2.3	6.2	3.2–10.3	6.3	0.9	7.7	3.7:1:4.7
Lettuce	3.2	1.5–5.8	1.2	0.3–2.0	6.0	4.0–7.7	2.3	0.8	4.8	2.8:1:5.2
Melon	4.4	2.5–6.4	1.3	0.5–2.5	5.7	2.5–8.0	3	1.7	5	3.3:1:4.2
Onion	3.4	2.2–4.6	1.5	0.4–2.7	3.8	1.8–5.3	2.7	1.3	2.7	2.3:1:2.6
Parsley	3.2	2.2–4.8	1.5	0.8–2.0	4.5	4.0–4.8	4.8	1.6	4.8	2.2:1:3.1
Radicchio	5.4	4.0–7.0	2.8	2.0–4.0	14.1	7.2–20.0	7	4	20	1.9:1:5.0
Radish	3.9	1.2–5.8	2.5	0.5–4.7	3.7	2.9–5.0	3	1	3	1.6:1:1.5
Savoy	5.1	3.7–6.5	2.1	1.7–2.5	5.2	3.3–7.0	5	2.1	5.5	2.5:1:2.5
Spinach	4.6	2.4–6.7	1.6	0.8–2.0	6.8	4.0–13.3	4.7	1.7	5	2.8:1:4.2
Strawberry	4.7	2.0–9.0	2.0	0.3–3.5	8.9	2.2–14.3	3.5	2.5	6.5	2.4:1:4.5
Pepper	4.5	3.0–8.0	1.3	0.6–2.5	6.5	4.4–13.5	3.9	1	5	3.5:1:5.0
Tomato	3.5	2.0–7.4	1.0	0.6–2.0	6.2	3.5–13.2	2.5	1	4	3.5:1:6.2
Watermelon	2.3	1.7–3.7	1.3	0.8–1.8	3.5	2.7–6.7	1.7	1.3	2.7	1.8:1:2.7
Zucchini	4.5	3.8–5.0	3.0	1.6–3.8	9.5	7.7–12.5	3.8	1.6	9	1.5:1:3.2

^a Regione Emilia Romagna GAP.
CRPV, 2010

contained in the soil prior to planting is known, then the total amount of N that has to be supplied to the crop during the whole growing period is estimated by simplifying Equation 3, as follows:

$$N_f = (Y \times f_N) - N_p \quad \text{Eq. 4}$$

The soil samples used for the extraction of NO₃⁻-N are not dried out but are used in wet conditions immediately after their selection to avoid N losses due to nitrification. If an immediate measurement is not possible, the soil samples have to be frozen to -20 °C. To express the soil N content on a standard basis, the moisture content of the soil is also determined using a subsample to allow for conversion of the measured values to mg of N per kg of dry soil. If the bulk density of the soil is known, the mineral N content in the soil can be converted into kg ha⁻¹.

Such balances, however, are actually simplified and may lead to misestimated N_f . For example, they do not consider some items on the N budget, such as the outflow related to the N losses through leaching, denitrification or volatilization, and the inflow due to N contained in water irrigation (Box 9).

In addition, they do not take into account the efficiency of utilization of applied N fertilizer. Although N in fertilizers is usually in forms rapidly available to plants, it is never fully utilized by the crop, even under optimal conditions. The crop takes up a part of the applied N, while a portion is left in the soil and lost through leaching, denitrification and volatilization. The fraction of fertilizer N taken up by the crops varies from 0.3 (Pilbeam, 1996) to more than 0.9 of N applied (Addiscott, 1996). It is affected by many factors, including type of fertilizer, timing of application, crop species, climate and soil conditions. To adjust the amount of N to apply to the crop, N_f would be divided by that fraction, as follows:

$$N_a = N_f / E_a \quad \text{Eq. 5}$$

where:

N_a = the adjusted amount of N supplied with fertilization (kg N ha⁻¹)

E_a = the efficiency of utilization of N applied (fraction)

BOX 9

How to calculate the N input from irrigation

A drip-irrigated tomato, grown on soil in a greenhouse in the Mediterranean area, requires frequent watering. Considering irrigation at an average rate of 12 litres m⁻² with water from an artesian well in which the NO₃⁻ concentration is 50 mg litre⁻¹, the NO₃⁻ supply to the soil can be calculated by the following formula:

$$\text{NO}_3^-(\text{kg ha}^{-1}) = V \times N \times (10\,000 \text{ m}^2 / 1 \text{ ha}) \times (1 \text{ kg} / 1\,000\,000 \text{ mg})$$

That is equivalent to:

$$\text{NO}_3^-(\text{kg ha}^{-1}) = V \times N \times 10^{-2}$$

where:

V is the irrigation rate (litre m⁻²) and N is the NO₃⁻ concentration in irrigation water (mg litre⁻¹)

In our case, the NO₃⁻ supply will be 6 kg ha⁻¹ for each watering. If irrigation is repeated 25 times during a 5-month growing season, the total input will be 150 kg ha⁻¹ of NO₃⁻, of which 22.6% (or in this case 33.9 kg) is N, an amount that should be taken into account in the N balance.

Since E_a is often uncertain, a so-called safety margin may be used. The safety margin is determined experimentally and its role is to prevent N shortage that might occur if only the amount of N required for uptake is present in the soil. It is an amount of supplemental N that takes into account both the fraction of fertilizer N taken up by the crop and N that could be lost by leaching and other processes. The safety margin varies with the crop from less than 30 to 90 kg N ha⁻¹; for crops with small, shallow roots, the safety margin is relatively large, while plants with long, deep, extensive root systems, and a long growing season require only a small safety margin. Thus, the adjusted amount of N to apply to the crop, N_a , will be calculated as follows:

$$N_a = N_f + SM \quad \text{Eq. 6}$$

where:

SM is the safety margin for the crop (kg N ha⁻¹)

Although the use of these adjusting factors improves N_f , its calculation maintains a high degree of uncertainty. For example, yields are forecast by taking an average of recent yield data from the field or area. But yields differ from year to year, and the true crop need for N is not known before harvest. Moreover, the values of crop N-uptake (f_N) vary widely in the literature.

On the other hand, the soil analyses used to determine the N soil content are based on the measurement of the mineral N (N_p) at the beginning of the growing season and an estimation of the N mineralization (N_m , N_r and N_s) during crop growth (pre-crop, organic matter content, organic fertilizer application etc.). However, for figures to be considered reliable, farmers need to perform frequent soil tests, which become costly and time-consuming. Nevertheless, the mineralization rate of SOM depends upon the temperature and moisture of the soil, as well as C/N; if not taken into account, the calculation will be imprecise.

Although application of the N balance sheet allows for a more reliable calculation of crop N requirement than a rule of thumb, other strategies should be pursued. Diagnostic tools in crop N management have recently been developed and applied, revealing several advantages in terms of reliability and cost-effectiveness (Gianquinto *et al.*, 2005 and 2011). These methods include the petiole sap nitrate test, the chlorophyll meter and test kits for soil analysis.

In Mediterranean greenhouses, all fertilizer N is often applied either preplanting or at the time of planting, or sometimes split in the early part of the growing season. This is an unsustainable way to manage the large amounts of N fertilizer supplied, as it frequently results in pollution and soil salinization.

In order to minimize such concerns – as well as reduce the costs of fertilizing – it is essential to increase nitrogen-use efficiency (NUE). NUE is a term used

to define the N fertilizer recovery in crop production, and may be expressed as kg of harvest product per kg of applied N. NUE can be improved and N losses minimized by supplying N at the right rate, right time, and with the right application equipment and method.

Correct N application entails a low N rate supplied at planting (starter rate of 20–40 kg N ha⁻¹), and the rest of N split in several applications during the growing season. The best results can be achieved by matching the N supply to the crop's requirements at each growth stage through variable rate application.

Fertilizer N should be placed close to the plant or band along the row; spreading application should be limited when sprinkler irrigation is used. If spread, fertilizer must be readily incorporated into the soil to avoid losses by volatilization. A sound method is distributing N through irrigation water (fertigation); this permits application of the nutrient whenever crops need it, precisely and uniformly to the wetted root volume (where the active roots are concentrated). Supplying N via foliar spray may also improve NUE, although this may involve several applications because of the low concentrations of N solution required to avoid damage.

Crop selection and soil management also influence NUE. In crop rotation, deep-rooted crops should follow shallow-rooted crops. Moreover, a period of bare soil should be avoided.

Phosphorus

In greenhouses, P requirements for plant growth and production are relatively large compared with in open fields. Nevertheless, over-supply of P may render other nutrients insoluble and therefore unavailable for plant uptake.

P uptake may be reduced by high pH in the root media. It is important to maintain media (hydroponic solutions, peat bags or other solid media) pH at 5.6–6.0 to favour P uptake. Furthermore, availability of P to plants is affected by soil temperature. For example, the uptake of P by tomato is drastically restricted at soil temperatures below 14 °C (Lingle and Davis, 1959). As a result, P deficiency may occur even in soils with adequate P levels if the soil temperature drops below 14 °C for extended periods.

Table 17 gives an overview of P input and P output. To decide the P fertilizer rates, the following balance can be applied (CRPV, 2010):

$$P_f = (Y \times f_P) \pm (P_{AV} \times C_{f_P}) \quad \text{Eq. 7}$$

where:

P_f = P (P₂O₅) supplied with fertilization (kg P₂O₅ ha⁻¹)

Y = expected crop yield (tonnes ha⁻¹)

TABLE 17

P budget of the crop: input adds P to the stock of available P in the soil; output removes P from the soil

Input of P	Output of P
Available P at planting ^{*a}	Uptake by the crop ^{*g}
Mineralization ^b	Immobilization ^h
Solubilization ^c	Fixation ^{*i}
P in organic manures (animal manure and compost) ^{*d}	Runoff ^j
P in crop residues ^e	Soil erosion ^j
P with fertilizers ^{*f}	

* Input-output relevant to greenhouse cropping systems.

^a The initial amount of available P in the soil at planting; it is measured by soil analysis.

^b The release of soluble inorganic P into soil through decomposition of phosphate-rich organic compounds. It is usually too slow to provide enough P for crop growth.

^c Solubilization of fixed P pool by plant roots and soil micro-organisms. It is usually too slow to provide enough P for crop growth.

^d Phosphates incorporated, e.g. with manures.

^e Only when the aerial part of previous crop has been incorporated into the soil. Usually it is removed to avoid risk of spreading diseases.

^f Phosphates (P₂O₅) applied as chemical fertilizers.

^g Uptake by crop is reported in GAP guidelines.

^h Assimilation of soluble phosphate by soil micro-organisms.

ⁱ The chance that fixation occurs needs to be minimized.

^j The P lost by water runoff and soil erosion is negligible in greenhouse if irrigation is managed correctly.

f_p = the amount of P(P₂O₅) that crop takes up for each tonne of produce (kg P₂O₅ tonne⁻¹ produce)

PAV = P available (P₂O₅) in the soil at planting as assessed through soil analysis (kg P₂O₅ ha⁻¹)

C_{f_P} = coefficient of P fixation in the soil calculated as follows:

$$C_{f_P} = a + (0.02 \times CaCO_3) \quad \text{Eq. 8}$$

where:

a is a coefficient related to soil texture (a = 1.2 for coarse, 1.3 for loam, 1.4 for fine-textured soils)

CaCO₃ is the total CaCO₃ (%) assessed through soil analysis

Soils with adequate P status usually need only a maintenance application related to crop removal, while soils with low P status may need substantial applications until an adequate soil P level for high crop yield is reached.

The chemical form of P in fertilizer materials is phosphate (H₂PO₄⁻, HPO₄²⁻ or PO₄³⁻). Phosphorus is generally supplied as normal (ordinary) superphosphate (0-12-0) and triple (concentrated) superphosphate (0-46-0), both excellent sources of P which also contribute Ca. Normal superphosphate also contributes S and often Fe. Other sources are monoammonium phosphate (11-52-0), diammonium phosphate (18-46-0), monopotassium phosphate (0-52-34), or a solution product such as ammonium polyphosphate (10-34-0).

In greenhouses, all fertilizer P is usually applied preplanting, and rarely partially localized along the row at the time of planting. An effective method is to distribute soluble fertilizers through irrigation water (fertigation), enabling application of P whenever needed.

The phosphate in fertilizers and manure is initially quite soluble and available. As phosphate ions enter a soil solution, most of them will react with the minerals within the soil. Phosphate ions generally react by adsorbing to soil particles or by combining with elements in the soil (Ca, Mg, Al and Fe). The adsorbed phosphate and the newly formed solids are relatively available to meet crop needs. Gradually reactions occur in which the adsorbed phosphate and the easily dissolved compounds of phosphate form more insoluble compounds that cause the phosphate to become fixed and unavailable. The conversion of available P to fixed P is partially the reason for the low efficiency of P fertilizers.

Adding P to the active P pool through fertilization will also increase the amount of fixed P. On the other hand, depleting the active pool through crop uptake may cause some of the fixed P to slowly become active P. Continued application of more P than is used by the crops increases soil fertility, but much of the added P becomes fixed and unavailable. Moreover, soils differ in their phosphate-holding capacity.

Another important feature is that organic matter dissolved in the soil solution competes with phosphate for binding sites on clay, counteracting P adsorption and increasing availability. Hence farming systems and rotations that bring much organic matter into soils contribute to a better use of soil and fertilizer P.

Potassium

Crops absorb potassium in the highest quantities (by weight) and it is for several reasons that this element needs special attention in greenhouse intensive cropping systems. As such systems are capital intensive, maximum yield and quality are required, and K is essential to both. Moreover, the demand for K fluctuates strongly according to the stage of growth, in particular for fruit vegetables.

To decide K fertilizer rates, the following balance can be applied (CRPV, 2010):

$$K_f = (Y \times f_K) \pm (K_{EXC} \times C_{f,K}) \quad \text{Eq. 9}$$

where:

K_f = K (K_2O) supplied with fertilization ($kg\ K_2O\ ha^{-1}$)

Y = expected crop yield ($tonnes\ ha^{-1}$)

f_K = the amount of K (K_2O) that the crop takes up for each tonne of produce ($kg\ K_2O\ tonne^{-1}\ produce$)

K_{EXC} = K readily available (K_2O) in the soil at planting as assessed through soil analysis ($kg\ K_2O\ ha^{-1}$)

TABLE 18
K budget of the crop: input adds K to the stock of available K in the soil; output removes K from the soil

Input of K	Output of K
Ready available K at planting ^{*a}	Uptake by the crop ^{*e}
K in organic manures (animal manure and compost) ^{*b}	Fixation ^{*f}
K in crop residues ^c	Leaching ^g
K with fertilizers ^{*d}	

* Input-output relevant to greenhouse cropping systems.
^a The initial amount of exchangeable K in the soil at planting; it is measured by soil analysis.
^b K incorporated, e.g. with manures.
^c Only when the aerial part of the previous crop has been incorporated into the soil. Usually it is removed to avoid risk of spreading diseases.
^d Potassium (K₂O) applied as chemical fertilizers.
^e Uptake by crop is reported in GAP guidelines (e.g. Table 16).
^f K trapped between the layers of certain kinds of clay minerals.
^g The K lost by leaching is negligible in greenhouse if irrigation is managed correctly.

C_{f_K} = coefficient of K fixation in the soil calculated as follows:

$$C_{f_K} = 1 + (0.018 \times A)$$

Eq. 10

where:
A is the clay (%) assessed through soil analysis

Sandy and organic soils require precise annual potassium applications since it is not possible to build up a high potassium reserve. If inadequate maintenance of K persists, soil productivity progressively diminishes. A crop’s ability to utilize N can also be restricted, resulting in increased potential for nitrate leaching.

The most common potassium fertilizer for use on field crops is potassium chloride (KCl). This is the least expensive source of potassium and is as effective as other materials for most cropping situations, except where very high rates are required, or where the solid content of potatoes is of primary concern. When high rates of potassium are needed or when soil salinity is a problem, potassium fertilizer applications should be split or materials with a lower salt index, such as potassium sulphate (K₂SO₄) or potassium magnesium sulphate (K₂SO₄•2MgSO₄), should be used.

Fertigation and its management

The term “fertigation” refers to the application of fertilizers with irrigation water. It involves connecting a fertilizer injector directly to the irrigation system. By adopting this approach to fertilize the crop, it is possible to supply correct levels of nutrients exactly and uniformly only to the wetted root volume, where the active roots are concentrated. This significantly increases fertilizer-use efficiency,

TABLE 19
Recommendation of the fertigation programme
for greenhouse tomato grown on sandy soil

Physiological stage	Concentration in the irrigation solution (ppm)		
	N *	P	K
Planting and establishment	120–150	40–50	180–220
Flowering	150–180	40–50	220–270
Ripening and harvest	180–200	40–50	270–300

* NH_4/NO_3 ratio = 0.3.
Imas, 2007

which means that the applied fertilizer rate can be reduced. This not only cuts the production costs but also reduces the potential of groundwater pollution, caused by the fertilizer leaching or accumulation of nutrients and salts in the topsoil.

Fertigation allows the adjustment of the amount and concentration of the applied nutrients according to the crop’s needs throughout the growing season. In order to supply nutrients to the crop effectively,

the farmer must know the optimal daily nutrient consumption rate during the growing season for maximum yield and produce quality (Scaife and Bar-Yosef, 1995).

Other advantages of fertigation are as follows (Imas, 2007):

- Savings are made in energy and labour.
- Timing of the application is flexible (nutrients can be applied to the soil when crop or soil conditions would otherwise prohibit entry into the field with conventional equipment).
- It is possible to conveniently use fertilizers also containing small concentrations of micronutrients which are otherwise very difficult to apply accurately to the soil.
- Nutrient supply can be regulated and monitored with precision.
- Fertigation is applied through the drip irrigation system, therefore crop foliage can be kept dry thus avoiding leaf burn and delaying the development of plant pathogens.

The soil texture is crucial for determining the volume of nutrient solution to distribute for each application. As a general rule (Enzo *et al.*, 2001), in coarse soils (e.g. sandy) fertigation volume should not exceed 200 ml per plant/emitter, to avoid nutrients leaching. In more fine-textured soils (e.g. clay), characterized by higher water-holding capacity and CEC, and less macroporosity, the fertigation volume should be increased to 300 ml per plant or more.

In any fertigation system, the basic components are: stock tanks for fertilizers, a water source, and an efficient delivery system (including devices for mixing fertilizer and water in correct proportions, and pumps to move the nutrient solution to the plants). Most growers use fertilizer injectors for applying fertilizers to greenhouse crops. These devices “inject” a specific amount of concentrated fertilizer solution (stock solution) per increment of irrigation water that passes through the injector. An important attribute of each fertilizer injector is the

injector ratio, which is defined as volumetric ratio of stock solution to dilute fertilizer solution (e.g. a 1:100 injector will deliver 100 litres of diluted fertilizer solution for each litre of concentrated stock solution that is metered through the injector).

In fertigation management, it is critical to ensure that the fertilizer is formulated properly. The grower must mix the correct amount of fertilizer so that the plants receive the right concentration (ppm, mg per litre) of the various nutrients. It is preferable to use single fertilizers and to match the supply of nutrients with the crop requirement, water quality and soil conditions. Formulation with compound fertilizers often results in a mismatch with the required ratios of individual elements.

It is important to have knowledge of the irrigation system established for the greenhouse:

- number of emitters and their flow rate
- diameter and length of main and secondary lines
- residual volumes in main and secondary lines
- water pressure

The flow rate is the quantity of liquid dispensed through the emitters within a given time (seconds, minutes or hours).

Considering a single-span greenhouse (10 × 50 m) for crops such as tomatoes, sweet peppers and cucumbers, about 12 drip lines are placed along the rows (about 0.82 m between lines). For these crops, the emitters (one emitter per plant) are spaced 0.4 m apart; therefore plant density will be around 3 plants m⁻² and the greenhouse will have 1 500 emitters. With lettuce, celery or other leafy vegetables, there are 15 drip lines, spaced about 0.66 m apart, and placed between the rows (plants at about 0.33 m between rows). For these crops, the emitters (1 emitter every 2 plants) are spaced 0.3 m apart; therefore plant density will be around 10 plants m⁻² and the greenhouse will have 2 500 emitters. On average, an emitter delivers 2 litres per hour, which is the daily water requirement per plant for most greenhouse crops. Therefore, if emitters are spaced 0.4 m and 0.3 m apart, the flow rate of the line will be 5.0 litres m⁻¹ and 6.66 litres m⁻¹, respectively. Thus, in the case of a tomato crop, the flow rate of the irrigation systems will be 3 000 litres per hour, while for lettuce 5 000 litres per hour.

Growers must accurately determine the amount of fertilizer needed to mix stock solutions. Most of the manufacturers of commercial fertilizers and fertilizer injectors have produced tables that simplify this task. Information is also provided on fertilizer bags. Without recourse to tables or bags, growers can use formulae to

calculate the amount of fertilizer needed. If the rate of fertilization to apply to the crop (in ppm), the percentage of N, P and K in the fertilizers, and the injector ratio are all known, then calculations are simplified by the following formula:

$$A = (C \times D)/(F \times 10)m \quad \text{Eq. 11}$$

where:

A = amount of fertilizer (g) to make 1 litre of stock solution

C = desired nutrient concentration (ppm)

D = dilution factor (the larger number of the fertilizer injector ratio)

F = % of element in fertilizer

As fertilizer analysis in fertilizer bags refers to the percentage of N, P_2O_5 and K_2O (e.g. 12-12-12 means 12% of N, 12% of P_2O_5 and 12% of K_2O), to correctly apply the formula the percentage of P_2O_5 and K_2O must be first converted into percentage of P and K as follows:

$$\%P = \%P_2O_5/2.3 \quad \text{Eq. 12}$$

$$\%K = \%K_2O/1.2 \quad \text{Eq. 13}$$

Example

A tomato is grown on a sandy soil, under a greenhouse with the characteristics reported above. The crop is starting to flower and the farmer is adopting the fertigation programme shown in Table 19. The injector ratio is 1:100 and the farmer wants to use monopotassium phosphate (0-52-34), potassium nitrate (13-0-46) and calcium nitrate (15.5-0-0) to supply 150 ppm (mg/litre) of N, 50 ppm of P and 220 ppm of K with each watering.

The first step is to calculate how many grams of each fertilizer need to be weighed out to make 1 litre of stock solution.

1. List all the variables to find out what is known and unknown:

Desired concentration in ppm = 150 N, 50 P, 220 K

Injector ratio = 1:100; dilution factor = 100

Fertilizer analyses = 0-52-34, 13-0-46, 15.5-0-0

2. Convert $\%P_2O_5$ to %P (Eq. 12) and K_2O to %K (Eq. 13) for monopotassium phosphate, and K_2O to %K for potassium nitrate:

$\%P = 52 \%P_2O_5/2.3 = 22.6 \%P$ in monopotassium phosphate (0-52-34)

$\%K = 34 \%K_2O/1.2 = 28.3 \%K$ in monopotassium phosphate (0-52-34)

$\%K = 46 \%K_2O/1.2 = 38.3 \%K$ in potassium nitrate (13-0-46)

3. Calculate how much monopotassium phosphate is needed to supply 50 ppm P applying Equation 11:

$$A = (50 \text{ ppm P} \times 100)/(22.6 \%P \times 10) = 22.1 \text{ g of 0-52-34}$$

4. Calculate the ppm K supplied by the amount of monopotassium phosphate determined in Step 3:

$$(22.1 \text{ g of 0-52-34}) \times (28.3 \% \text{K in 0-52-34}) = 6.26 \text{ g K in 0-52-34}$$

To know the concentration (ppm) of K in nutrient solution, the farmer must convert grams to ppm and divide by the dilution factor (100):

$$(6.26 \text{ g K} \times 1\,000 \text{ mg litre}^{-1})/100 = 62.6 \text{ ppm K}$$

About 63 ppm K is supplied by monopotassium phosphate.

5. Since the farmer desires 220 ppm K and monopotassium phosphate supplies only 63 ppm K, farmers must make up the rest of the K with potassium nitrate. Therefore:

$$220 \text{ ppm K} - 63 \text{ ppm K} = 157 \text{ ppm K needed from potassium nitrate}$$

6. Determine the amount of potassium nitrate needed to supply 157 ppm K:

$$A = (157 \text{ ppm K} \times 100)/(38.3 \% \text{ K} \times 10) = 41.0 \text{ g of 13-0-46}$$

7. Calculate the ppm N supplied by the amount of potassium nitrate determined in Step 6:

$$(41.0 \text{ g of 13-0-46}) \times (13 \% \text{ N in 13-0-46}) = 5.33 \text{ g N in 13-0-46}$$

To know the concentration (ppm) of N in nutrient solution the farmer must convert grams to ppm and divide by the dilution factor (100):

$$(5.33 \text{ g N} \times 1\,000 \text{ mg litre}^{-1})/100 = 53.3 \text{ ppm N}$$

About 53 ppm N is supplied by potassium nitrate.

8. Since the farmer desires 150 ppm N and potassium nitrate supplies only 53 ppm N, farmers must make up the rest of the N with calcium nitrate. Therefore:

$$150 \text{ ppm N} - 53 \text{ ppm N} = 97 \text{ ppm N needed from calcium nitrate}$$

9. Determine the amount of calcium nitrate needed to supply 97 ppm N:

$$A = (97 \text{ ppm N} \times 100)/(15.5 \% \text{ N} \times 10) = 62.6 \text{ g of 15.5-0-0}$$

10. Thus farmers must add 22.1 g of monopotassium phosphate (0-52-34), 41.0 g of potassium nitrate (13-0-46), and 62.6 g of calcium nitrate (15.5-0-0) for each litre of stock solution. That means 125.7 g of fertilizer for each litre of stock solution, and 1.257 g of fertilizer for each litre of diluted nutrient solution when using a 1:100 injector. This will supply 150 ppm of N, 50 ppm of P, and 220 ppm of K with each watering.

The next questions are how much would the total volume of nutrient solution dispensed under the greenhouse be (and therefore the total volume of the stock solution), and how long would the watering last to distribute all the nutrient solution to the tomato crop?

In sandy soil it is advised to distribute no more than 200 ml nutrient solution to each emitter/plant to avoid nutrient leaching. Therefore:

1. The farmer will calculate the amount of nutrient solution needed to feed 1 500 plants each watering:

$$(200 \text{ ml nutrient solution}) \times (1\,500 \text{ plants}) / (1\,000 \text{ ml litre}^{-1}) = 300 \text{ litres of nutrient solution}$$

2. The farmer will calculate the amount of stock solution mixed by a 1:100 injector:

$$(300 \text{ litres of nutrient solution}) / 100 = 3 \text{ litres of stock solution.}$$

Thus farmers must prepare 3 litres of stock solution adding 66.3 g of monopotassium phosphate (0-52-34), 123.0 g of potassium nitrate (13-0-46) and 187.8 g of calcium nitrate (15.5-0-0). This means 45.1 g of N, 15.0 g of P and 65.8 g of K.

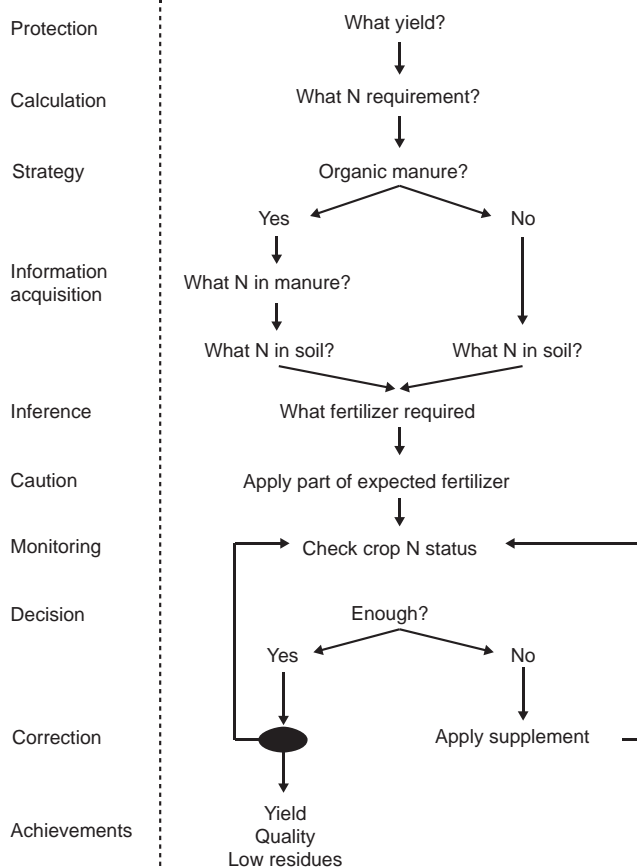
3. Then, the farmer determines the watering time, considering that the flow rate of the irrigation system is 3 000 litres h⁻¹:

$$(300 \text{ litres of nutrient solution}) / (3\,000 \text{ litres h}^{-1}) \times (60 \text{ min h}^{-1}) = 6 \text{ min}$$

In a single-span 10 × 50 m greenhouse, 6-minute fertigation with the calculated stock solution, using a 1:100 injector, is sufficient to feed the tomato crop with 45.1 g of N, 15.0 g of P and 65.8 g of K (equivalent to about 0.9 kg ha⁻¹ N, 0.3 kg ha⁻¹ P and 1.3 kg ha⁻¹ K). The farmer must check if these match the daily consumption rate of tomato at its physiological stage. If not, the application must be repeated during the day.

During the crop cycle, especially for short-term crops like bedding plants, it is important that the farmer measures the electrical conductivity (EC) of the fertilizer solution on a weekly basis to check that the injector is working properly.

FIGURE 3
N fertilizer requirements



GAP recommendations

Cropping systems and fertilizer recommendations differ between regions but some general rules are valid:

- Plant nutrients are absorbed by the roots and eventually assimilated in order to sustain plant metabolism and growth.
- Seasonal variation in nutrient requirements depends on crop ontogeny. Nutrient uptake ratios change according to developmental stage as a result of variation in the growth rate of different plant organs, which have different mineral compositions.
- The rate of mineral uptake is related to the rate of crop growth and tends to decline with plant age, as does the critical nutrient concentration of plant tissues.
- Soil N-P-K supply derives from the mineralization of old organic matter and the addition of fresh material (e.g. crop residues, organic manure). Therefore fertilizer recommendation systems need to estimate this input.

GAP recommendations (cont'd)

- When growth is stimulated by increasing irradiation and water uptake, it is important to supply more minerals.
- Remobilization of nutrients stored in old or adult leaves makes little contribution to the mineral requirements of growing organs in greenhouse crops; the synchronization of fertilization to actual mineral uptake is crucial for optimal crop growth.
- Overfertilization results in excessive consumption and has many drawbacks.
- Optimal fertilizer supply ensures unrestricted growth and a yield that is close to potential, while minimizing losses to the environment.
- Vegetable quality is at its best when fertilizer supply matches crop requirement over the length of the growing season. Therefore:

Estimation of the crop's nutrient requirement is very important for both economic and environmental reasons.

Thus:

- Knowledge of expected crop yield is crucial to estimate total nutrient requirements and avoid overfertilization.
- Knowledge of actual crop water uptake (or transpiration) may provide a useful tool for real-time estimation of crop growth and, hence, nutrient requirements.
- Prevention of nutrition imbalance is important: visually monitor crop mineral status day-by-day and analyse, at regular intervals, soil and leaf tissues and, in soilless culture, growing medium and nutrient solution.
- Soil mineral status at the start of the growing season is a good starting point for fertilizer recommendations.
- Soil tests, carried out before planting, provide an estimate of the amount of fertilizer to be applied; plant analyses can then be used to monitor crop nutritional status throughout the growing season, allowing adjustment for errors in fertilization.
- For assessment of soil nutrient concentration, follow specific sampling procedures for both pattern of sampling and sample size to give adequate spatial coverage.
- For assessment of plant nutrient concentration, follow standard recommended procedures for sampling whole plant or plant parts. Collect the right plant part at the right time (within the day or the growing season) for the specific nutrient to be assessed.

Consider:

- Splitting the supply of fertilizers throughout the growing season greatly increases the opportunity to match total supply to actual requirement for fertilizer, lessens the nutrient loss from agricultural land, and reduces risk of soil salinization.

It is therefore crucial to enhance the efficiency of fertilizer applications:

- Apply at least part of the fertilizers during crop growth in accordance with crop nutritional status.
- Apply fertilizers via fertigation.

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11. Growing media

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INTRODUCTION

In Mediterranean countries, most protected cultivation growers use soil – often associated with soil pests, salinity problems and excessive application of pesticides (nematocides, fungicides, insecticides and herbicides). Residues can be a danger to human health (for both consumers and producers) and often lead to environmental pollution. Several techniques have been introduced to the region to overcome such problems with minimum negative impact on the environment and human health: soil fumigation using solar energy, use of grafted seedlings and soilless culture.

This chapter examines growing media used in soilless culture; they represent one of the main solutions for soil problems, have positive effects on the environment and improve fertilizer and water-use efficiency. This is especially the case in Mediterranean countries where shortage of good quality water is a major constraint in protected cultivation. At present, a relatively small proportion (approximately 10%) of growing media – which are very important for a good start to plant cultivation – can be used for the production of seedlings and transplants.

The cultivation of plants in systems without soil *in situ* is defined in literature as “soilless culture” (Gruda, 2009). Many such systems are based on the use of solid rooting media for growing plants. They are usually called “growing media” or “substrates”; however, sometimes terms like “aggregate systems”, “supporting media” or “potting soil” are used. With reference to plant cultivation and propagation, “growing media” or “substrates” are defined as all those solid materials, other than soil, which alone or in mixtures can guarantee better conditions than agricultural soil (for one or more aspects). Hence, media of different origin take on the role of soil and provide anchorage for the root system, supply water and nutrients for the plant, and guarantee adequate aeration in the root area (Gruda *et al.*, 2006).

Growing media are used in containers (organic substrates, perlite etc.). However, sometimes they are used in the form of prepared cubes (rockwool cubes for seedling and transplant production), bags and slabs (peat-based substrates and rockwool, respectively), mats (polyurethane foam) and troughs (rockwool); these last three are also used for vegetable production in soilless culture systems.

While development is very country related, from a historical point of view the development of growing media can be expressed in distinct steps (Gruda, 2012a):

- Until the 1950s, horticulturists used gardening soil – mixtures of own composted organic waste and mineral soil, used both for plants with bare roots and for plants with root balls.
- In the 1950s, peat culture substrates, mixed with clay or alone, were developed. These substrates became established in the 1960s and peat became the main component of growing media.
- In the mid- to late 1970s, rockwool substrate spread throughout Western Europe and became important for vegetable cultivation. Tomatoes, cucumbers and bell peppers were grown in rockwool slabs, wrapped in plastic film. Rockwool is still one of the most popular growing media in vegetable soilless culture.
- In the 1980s and 1990s, specific mixtures for specific plants were produced from peat – the ease of rockwool cubes and slabs was combined with good growing properties.

The development and refinement of growing media in horticulture in the 1980s and 1990s coincided with increased ecological awareness. In recent years, many innovative cultivation procedures using new growing media methods have been developed, including systems without a solid medium, as well as aggregate systems in which inorganic or organic substrates are used (Gruda, 2009). Different materials can be used as growing media offering numerous advantages:

Compared with water culture and aeroponics:

- reservoir for water and plant nutrients
- adequate oxygen exchange
- anchorage or support for plant
- lower rhizosphere temperature excursion

Compared with natural soil culture:

- standardization
- light weight
- virtual absence of pests
- cultivation without soil

There are also disadvantages compared with on-soil cultivation:

- volume limitation
- balanced fertilizer ratios requirement
- potential expense
- rapid development of deficiency symptoms

CHARACTERISTICS OF GROWING MEDIA

When choosing a growing medium, knowledge of its characteristics (physical, chemical and biological) is very important, because they affect plant response and production cost. Absence of pests and pathogens is essential; biostability and biological inertia are other parameters to be taken into consideration, particularly when long cycles are carried out or the growing medium is reused during successive growing cycles. There are different national and international standard methods used for the investigation of substrates. In order to simplify international information exchange, the ISHS (International Society for Horticultural Science) method is suggested as a standard.

Physical properties

The physical properties of substrates give important information concerning numerous parameters, for example: water/air ratio (required for proper regulation of irrigation); and volume weight or bulk density. On the basis of such parameters, it is possible to make further calculations of the substrate's mineral content (Gruda and Schnitzler, 1999a; Gruda and Schnitzler, 2004a). Furthermore, it is important to know water distribution and movement at root level.

The fact that growers cannot affect a target change of the physical characteristics of substrates or substrate mixtures within a culture means that it is essential to select the correct substrate before cultivation starts (Verdonck and Demeyer, 2004). Given that the volume of growing media in the containers is relatively small, the requirements regarding a substrate's physical properties and their standardization are very high.

Besides the standard ISHS method, the negative or positive pressure method (mostly used for the investigation of water content in mineral soils) can also be used for the investigation of a substrate's physical properties. Gruda and Schnitzler (1999a) found close relationships between the modified ISHS method and the two other methods at $pF = 1.0, 1.7$ and 2.0 . Other methods are used as industrial standards in certain countries, for example, CEN (European Committee for Standardization) in the EU region.

Volume weight or bulk density (g/cc)

Dry mass per unit volume is related to discrete mineral particles and to amorphous compounds, the latter represented by organic matter. As some media are composed

of more than one ingredient, the characteristics of each ingredient contribute to the total of volume weight of the medium (Raviv *et al.*, 2002). Moreover, the quantity of organic substrate in a container (in some degree inorganic as well) can be affected by substrate compression. Different volume weight can lead to different physical properties as well as to diverse nutrient levels in the substrate. Therefore it is recommended to determine the volume weight on the basis of real container/pot conditions (Gruda and Schnitzler, 1999a).

Although it depends on origin and grain size, the average volume weight of peat materials is 0.09–0.20 g cm⁻³ (RAL, 1999). However, the requirements in relation to volume weight and substrates for containerized horticultural plants, e.g. for transplant production, depend on the production system and technology adopted. Volume weight affects the choice of substrates in various ways. For example, to prevent container instability in windy conditions, high volume weight media are required, while for frequently irrigated high intensity greenhouse crops, media of low volume weight are required (Raviv *et al.*, 2002; Wallach, 2008). Low volume weight is also important when transporting growing media.

Particle size

The array of particles can be divided into groups according to size, and the medium solid phase as a whole can be characterized in terms of the relative proportions of its particle size groups. The size and shape of particle size distribution are useful for estimating the hydraulic properties of the media, such as water retention and hydraulic conductivity (Wallach, 2008).

Gruda and Schnitzler (2006) observed a close relationship between the amount of solid particles < 1 mm and the water-holding capacity of substrates. For example, for a fine wood fibre substrate used as a component for production of press pots for vegetable seedlings, the maximum water capacity with 100 percent of particles < 1 mm was about 95 percent, while a complete absence of these particle sizes resulted in maximum water capacity of 70 percent. Therefore, it is possible to control the maximum water capacity by the quantity of fine particles.

Porosity

A growing medium, like soil, consists of three phases: solid, aqueous and gaseous. The pores are filled with air or water according to pore dimension and water content in the substrate. Although the porosity or total pore space (TPS) does not account for pore size distribution or water and air content in the pores, it is often used when characterizing substrates. The TPS of substrates is higher than in soils, where it is approximately 50 percent of the volume. De Boodt and Verdonck (1972) and Fonteno *et al.* (1981) point out that an ideal substrate should have a TPS of over 85 percent. In general, depending on shape, arrangement and particle size, organic substrate TPS is about 85–95 percent (Michiels *et al.*, 1993), while other growing media contain 60–90 percent (Raviv *et al.*, 2002). Analyses

generally result in negative correlation of porosity and volume weight of growing media. However, the volume weight cannot accurately determine TPS if components with closed pores, such as perlite, pumice or expanded clay, are used (Bunt, 1976; Wallach, 2008). Plate 1 shows the closed porosity of an expanded clay granule after breakage.

Water and air ratio and pore size distribution

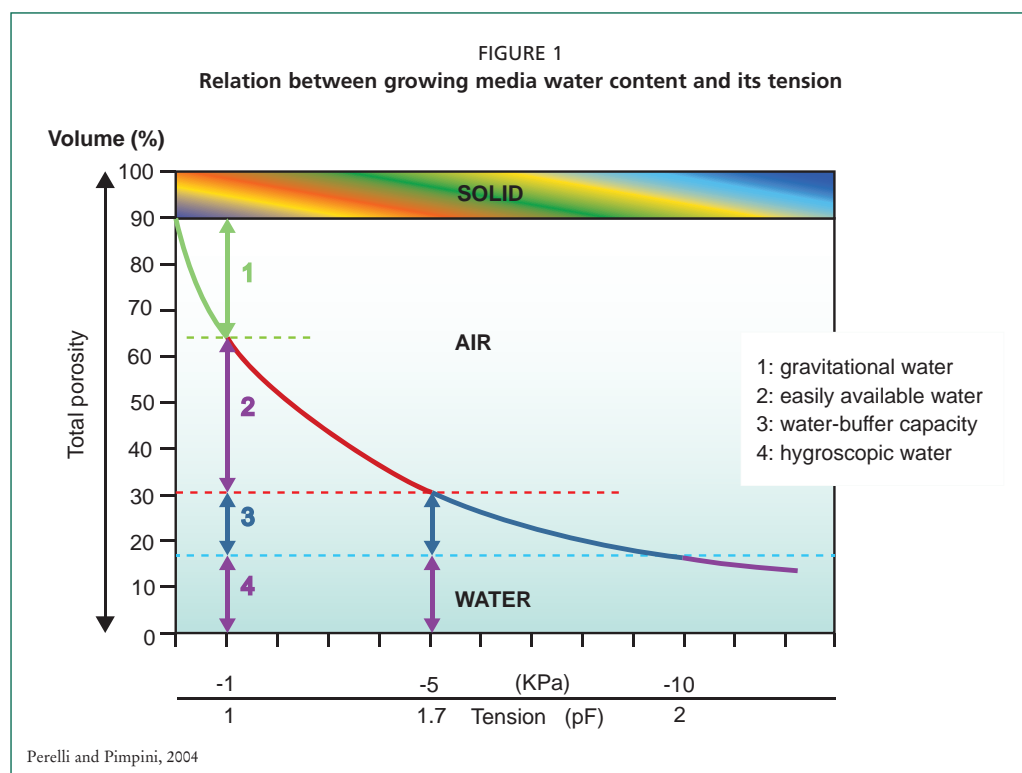
Water and air volume are the most important physical parameters for substrates (Bunt, 1976). Water must be available in the substrate at the lowest possible energy status while maintaining sufficient air supply in the root zone. The two parameters are antagonistic: if the pores are filled with water, air is missing and vice versa (De Boodt *et al.*, 1974). The volume of water that saturates a given volume of substrate is defined as its effective pore space (EPS) or air volume. The difference between TPS and EPS constitutes the volume of closed pores that are not accessible by water (Raviv *et al.*, 2002).



Plate 1
Expanded clay closed porosity

Container capacity (also known as “water-holding capacity”) is the amount of water remaining in the container after water stops draining following saturation. The water content for growing media is usually defined at water suction of 1 kPa or at $pF = 1.0$. Water-holding capacity is one of the most important aspects to consider in irrigation frequency and volume management. However, within the same growing media, a given volume can hold a different amount of water when gravitational water stops draining. While “container capacity” and “water-holding capacity” are sometimes used as synonyms, container capacity is the total volume of water in the container, and water-holding capacity is the water content at $pF = 1.0$ (Gruda, 2005). Higher containers signify a higher water column (Fonteno *et al.*, 1981; Karlovich and Fonteno, 1986; Martinez *et al.*, 1991; Milks *et al.*, 1989; Gruda and Schnitzler, 2004a). Therefore, relatively less water is held by capillarity and adhesive forces and more water is drained by gravity (Gruda and Schnitzler, 2006). The upper layers of the substrate hold a lower amount of water, while potential water availability is much higher at the container bottom (Figure 1).

Gravitational force is higher in the upper part of the substrate; consequently, the water-holding capacity is lower in taller containers. Taller cells or containers have a larger percentage of TPS space, even if the same growing media or substrate mix is used.



Therefore, when considering a different water-holding capacity in relation to container shape and height, it is generally better to speak of container capacity rather than field capacity. To this end, the container zoning concept (accounting for moisture characteristics and container geometry) is introduced to quantify the water-holding capacity.

One criterion for substrate classification is the quantity of free water that can be delivered to the plant roots at different water potential levels. However, not all the water in the growing media is available to the plant. According to Figure 1, the following types of water can be found in the substrate:

- Gravitational water (number 1 in Figure 1) – not held in the substrate and moves in response to gravity (the amount of free water in the pF range 1.0–2.0 [–1––10 kPa] is an important parameter for substrate cultures).
- Easily available water (EAW) (number 2) – directly available to plants (the amount of free water when pF increases from 1.0 to 1.7 [–1––5 kPa], it fills pores of 60–300 μm).
- Water-buffering capacity (WBC) (number 3) – serves as a reserve, when the plants transpire intensively (De Boodt and Verdonck, 1972) (the amount of free water when pF increases from 1.7 to 2.0 [–5––10 kPa], it fills pores of 30–60 μm).

- Less readily available water – the amount of free water calculated when water tension increases from $pF = 2.0$ to 4.2 .
- Unavailable water – water held by media at tensions of $pF > 4.2$ and the plant cannot remove it.

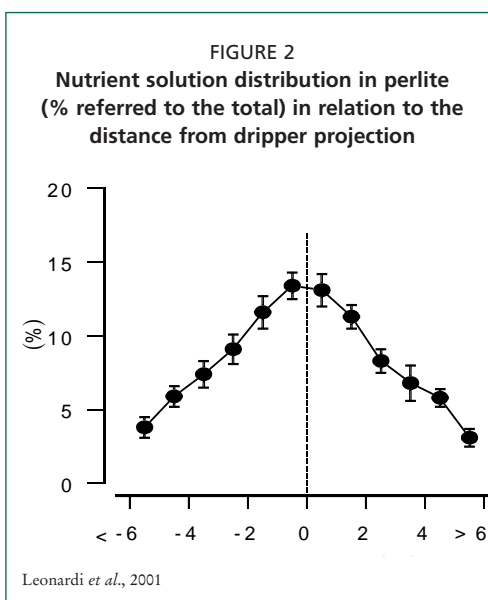
Large pores generally favour rapid drainage and adequate aeration for plants, while water is mainly held in small pores. Therefore, adequate pore size and distribution are critical for a good medium. However, other factors also have an impact. In wood fibre substrates, the pore size distribution of a growing medium is not only influenced by substrate type, but also by particle size, substrate compression (and consequently real volume weight), container size and height, volume loss during a growth cycle, and plant growth and root development (Gruda and Schnitzler, 2004a).

Hydraulic conductivity (cc/min)

The saturated hydraulic conductivity (K_{sat}) of a substrate is an indicator of drainage behaviour, also referred to as permeability, permeability factor, flowing rate and filter rate. Drainage behaviour is mainly defined by the percentage of macropores. Higher K_{sat} implies a higher percentage of macropores, while destruction of these pores leads to decreased K_{sat} (Gruda and Schnitzler, 2004a). According to Raviv *et al.* (2002) particles of smaller-sized individual grains have a larger specific surface area, increasing the drag on water molecules that flow through the medium. Therefore water flows off fastest in coarse growing media, followed by substrates and mixtures with smaller-sized particles.

What is more, in growing media with higher hydraulic conductivity, the water/nutrient solution passes more through the central part of the substrate near to the irrigation dripper and progressively less through the part of the substrate located closer to the container walls (Figure 2). This uneven distribution of nutrient solution in the substrate, apart from affecting the uptake of nutrients and water, can determine variations in electrical conductivity and pH in different parts of the rhizosphere.

Furthermore, as micropores increase, so does pore continuity. This can be documented through the pore tortuosity. Pore tortuosity represents a fitting factor and is linked to the fact that some of the pores are clogged up and that the real pathway for waterflow is longer than



the apparent one (Caron and Nkongolo, 2004). For peat substrate, the pore tortuosity was found to be closely correlated with the plant growth of *Prunus × cistena* sp. (Allaire *et al.*, 1996). Changes in tortuosity can also result from sample disturbances.

Thermal characteristics are mainly related to thermal conductivity and thermal diffusivity. It is important to know the possible effects of these characteristics on growing media and consequently on root temperature; they should be considered in relation to the water-holding capacity of the substrate, which in turn affects the apparent specific heat ($\text{cal C}^{-1} \text{cm}^{-3}$).

Chemical properties

For the evaluation of the chemical properties of a growing medium, the most important criteria are pH value, cation exchange capacity (CEC), salt concentration and nutrient content (macro- and microelements).

TABLE 1
pH value of different substrates

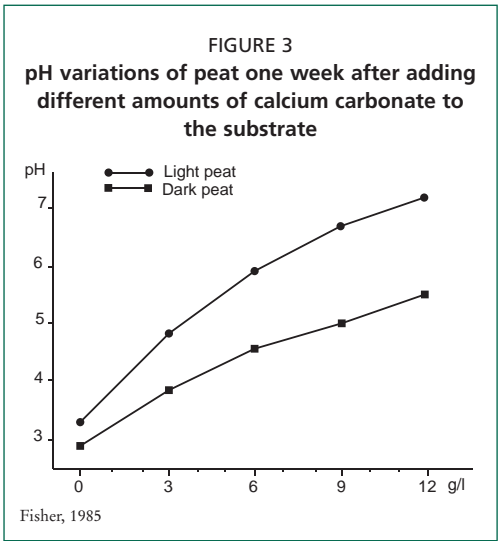
Substrate	pH value
Expanded clay	4.5–9.0
Peat	3.0–7.3
Perlite	6.5–7.5
Pumice	6.7–9.3
Sand	6.4–7.9
Vermiculite	6.0–7.2
Volcanic tuff	7.0–8.0

Gianquinto and Pimpini, 2001

pH value

pH plays an important role in plant substrates, determining the availability of various nutrients. Although plant pH requirements differ, for most plants optimal nutrient availability occurs when the pH value of a nutrient solution is between 5.5 and 6.5. Higher values, even $\text{pH} > 6.0$, nearly always reduce the solubility of phosphates, iron and most micronutrients. Moreover, high pH values (> 7.5) in the irrigation water are undesirable, given the probable precipitation of Ca and Mg carbonates, as well as orthophosphates, which can clog the drippers.

The pH value of the nutrient solution can also be important for the interaction between orthophosphate ions and solid constituents. Thus, low P availability may restrict crop productivity even shortly after P application (Raviv *et al.*, 2002). Significant variations in pH can occur for some substrates, depending on their provenance (Table 1). Therefore, correction may be advisable, taking into account the different reactions of the considered substrates (Figure 3).



In general, lower pH value and lower nutrient and salt content are better for substrate preparation and production. Initial materials with such characteristics (e.g. peat moss) permit substrate manufacture where:

- the pH value can be increased easily by lime addition;
- it is possible to regulate and balance the relatively high pH value of other component materials; and
- the demands or requirements of different cultures can be accurately taken into account, produced and controlled (Gruda, 2005).

Furthermore, it should be considered that pH values for some organic growing media (e.g. pine tree substrates) change during the storage process (Jackson *et al.*, 2009). It is therefore recommended to analyse the substrates immediately before plant cultivation and if necessary to adjust the pH value for optimal plant growth.

Cation exchange capacity (CEC)

CEC gives information about the sorption force and buffering ability of a substrate for nutrients. Substrates with high CEC can store more nutrients and plants are fertilized more intensively. In addition, such substrates buffer the fertilizer or mineral materials better when hard water is used (Gruda, 2005). CEC is considered an important substrate characteristic when nutrient solution is not continuously offered and solid fertilizers are used. The growing media composition is important; continuous fertigation of on-substrate-grown crops enables the use of different substrates with different CEC. For example, the CEC of growing media can be very low (CEC ~1.5–3.5 meq/100 g, e.g. perlite) or high (CEC ~100–180 meq/100 g, e.g. sphagnum peat). However, even inert substrate accumulates organic compounds (e.g. plant roots or decomposed materials during the growth process) which can build up surface charge.

From a practical point of view, considering the small volumes of growing media used for vegetable production, high CEC growing media also lead to limited nutrient-buffering capacity; however, frequent fertigation can mitigate the negative effects.

Salt concentration

Growing media can sometimes have a relatively high salt concentration, for example, when the organic or mineral materials used as a substrate are collected from an area with significant salt sources (e.g. close to the sea). In these cases, excess salt leaching is required prior to substrate use.

Excess salt concentration can also be observed in organic substrates when high rate organic matter decomposition occurs. In most situations, the rate of release of mineral salts is about the same as the rate of uptake by the plants. Therefore, there is no excessive build-up (Handreck and Black, 2005). However, when materials

that decompose easily are adopted, problems can be observed. In vegetable production the risk is not so frequent because the seedling production period is too short to determine such an effect, and in soilless cultivation it is not advisable to adopt unstable organic substrates, because decomposition would correspond to outstanding variation of substrate physical characteristics.

Biological properties

A good growing media must be free from pests and pathogens, biologically stable and not toxic.

Phytotoxicity

The use of forestry products (bark, sawdust, woodchips) as well as compost container substrates can involve problems of phytotoxicity. Phytotoxicity depends on the chemical composition of the substrate, which in turn can cause salinity, nutritional disorders and enzymatic or hormonal metabolic alterations (Ortega *et al.*, 1996). High potassium and manganese content (Maher and Thomson, 1991) and the presence of phenolic compounds (Ortega *et al.*, 1996), terpenes, organic acids and fatty acids (Morel and Guillemain, 2004) can be the cause of such problems (Gruda *et al.*, 2009).

Gruda and Schnitzler (2004b) report no plant growth inhibition when bark content in fresh pine or spruce wood fibre substrate is approximately 5 percent. On the contrary, a higher amount of fresh bark negatively affects plant growth. Using hardwood sawdust as a growing medium, it was found that the wood contained phytotoxins, which in return affected plant growth (Maas and Adamson, 1982). Indeed, these compounds have a protection effect and defend woods against insects or infections; therefore, they are toxic to other organisms, such as greenhouse plants cultivated in substrates originating from those materials (Gruda *et al.*, 2009).

Methods such as composting, ageing, leaching, washing, mixing and fertilization have been used to reduce or eliminate phytotoxicity properties (Ortega *et al.*, 1996; Gruda *et al.*, 2000). Gruda *et al.* (2009) reported that extracts from pine tree substrates produced by grinding loblolly pine tree (*Pinus taeda* L.) reduced the germination rate and radicle growth of tomato and lettuce; however, after washing, an improvement was recorded for radicle length of both species. Pre-treatments (e.g. substrate washing) can be recommended for use in the manufacturing process for pine tree substrates or by growers before planting.

Several authors have reported that the growth of fungi on woody tissues in solid-state fermentations on pine chip fermentations decreased toxicity (Dorado *et al.*, 2000; Linares *et al.*, 2003).

N-immobilization

The transfer of inorganic N-compounds into micro-organism bodies through nitrogen consumption and their reservation is known as N-immobilization. Net N-immobilization occurs in organic materials because of the wide range of C/N ratio, for example: in waste paper 135 : 1, in straw 50–100 : 1, in crusts 75–117 : 1, and in wood fibre substrates 100–272 : 1 (Gruda *et al.*, 2000).

Optimal plant growth is ensured only if sufficient nitrogen is available for both micro-organisms and plants (Handreck, 1992); different solutions have been developed for reducing N-immobilization. Composting makes it possible to use waste bark or wood as a substrate; while this process stabilizes the organic substances, it takes a long time and can lead to loss of raw material (Handreck, 1992; Prasad, 1997b).

Other methods involve adding supplemental substances to substrates to eliminate the “weaknesses” of natural wooden materials: for example, hydrolysis of woodchips under pressure in the presence of acids (Lemaire *et al.*, 1989). Using this method, the lignin-cellulose ratio in wood changes from 1 : 2–3 to 1 : 1–2. The supply of nitrogen and other mineral additives prior to manufacturing fibre substrates under high pressure and heat in the presence of water vapour, in order to improve substrate properties, is called “impregnation” (Penningsfeld, 1992).


GROWING MEDIA CLASSIFICATION AND CHOICE

Numerous plant substrates are used in various types of soilless culture systems. Moreover, new materials have been introduced worldwide. The international trend for substrate development tends towards the use of natural resources and renewable raw materials (Gruda, 2005).

Given their diversity, the classification of growing media helps growers make the right choice. Growing media are generally classified into organic and inorganic materials. Inorganic substrates can come from natural sources as well as processed materials; organic growing media can be synthetic (e.g. polyurethane) or natural organic matter (e.g. peat, wood-based substrates). Growing media can also be classified as fibrous (e.g. coir) and granular (e.g. perlite). Bearing in mind that important properties of growing media include their chemical characteristics, they can also be classified as active (e.g. peat) or inert (e.g. rockwool and sand). Herein is described the classification into organic and inorganic materials.

The choice of a substrate for soilless cultivation has technical and financial implications. There is no univocal scheme for the choice of growing media. In several areas where on-substrate cultivation is exploited, growers try to adopt local factory-manufactured products, or locally available cheap substrates, even when there is insufficient information about their physical and chemical characteristics and, consequently, their management.

Choosing a substrate



Desirable properties:

- Low volume weight
- Good reserve of easily available water and good aeration
- Good rehydration properties after drying
- Stable structure
- Good buffering capacity for an optimal pH
- Appropriate pH properties for the crop
- Uniform from batch to batch
- Free of phytotoxic compounds
- Low micro-organism activity
- Pest- and pathogen-free

Aspects to be considered:

- Availability of information on chemical and physical characteristics
- Type of soilless system adopted
- Shape and volume of the container
- Reusability
- Costs

The choice of a given growing medium without standardization does not guarantee correct nutrient solution management, given the more or less notable differences in substrate typology, provenance and batch. For a correct choice of growing media, some desirable properties should be considered, but it is rare to find growing media with all these properties, and in some cases pH correction, disinfection or substrate mixing is advisable to achieve the desired properties. Growing media mixtures are generally used in vegetable soilless greenhouses and in the seedling and transplant industry; they consist of growing media constituents and additives. Growing media constituents include a range of raw materials; general combinations include peat and other organic or inorganic materials and are formulated on a percentage volume basis. Growing media additives include fertilizers, liming materials, biocontrol or wetting agents, and are formulated on a weight basis. It is recommended to use finished products, not to experiment with self-produced mixtures.

Furthermore, the above properties assume importance according to the growing system adopted. Continuously fertigated crops do not necessarily require growing media with a high cation exchange capacity, compared with potted plants and containerized crops. For closed systems (comparison with open systems), a

low water-holding capacity does not represent a problem, as it is possible to adopt frequent irrigation without loss of leached nutrient solution which is recycled. Moreover, for subirrigated crops, the suitability of the substrate in allowing capillary rise is very important for an appropriate distribution of nutrient solution in the growing media. In addition, other aspects related to the availability of water and electric power should also be taken into consideration; for example a blackout of a few hours (frequent in country areas) may prove particularly dangerous when a substrate with a low holding capacity is used.

Inorganic growing media

Besides rockwool, various inorganic substrates, such as perlite, tuff (a volcanic porous rock), expanded clay granules and vermiculite, as well as synthetic materials, have been used as growing media (Gruda *et al.*, 2006).

While in older installations, mainly gravel and sand were applied to improve aeration, nowadays lighter materials (e.g. rockwool, originally produced for thermal and acoustic insulation in the construction industry) are widely used (Raviv *et al.*, 2002; Gruda *et al.*, 2006).

Rockwool

Polythene-wrapped rockwool, thanks to its light weight and ease of handling, has become the dominant soilless culture system in Europe and is used throughout the world for both flowers and vegetables, e.g. tomatoes (Plate 2) (Gruda *et al.*, 2006). In addition, cubes or blocks of different sizes are used for seedling and transplant propagation and granulated rockwool is used as a component of potting mixtures. Rockwool is manufactured by melting basaltic rock with limestone and coke at high temperatures and spinning the melt into fibres. Afterwards the fibres are bound together by heating them with additives. Rockwool has a low volume weight of approximately $0.07\text{--}0.1\text{ g cm}^{-3}$ and a TPS of 92–97 percent. The main chemical characteristic of rockwool is that it is totally inert, except for some minor effects on pH. The initial pH of the material is rather high (7.0–8.0) and a pH adjustment is therefore required (Smith, 1987). Generally, the setup of a rockwool growing system is simple: rockwool slabs are placed in the rows, holes for plants are cut in the plastic surrounding the slabs, and the slabs are filled with



GRUDA, 2010

Plate 2

Greenhouse tomato plants, cultivated in rockwool slabs

solution. After soaking for about 24 hours, the transplants are placed on the slabs with drainage slits cut at the bottom. A complete nutrient solution is supplied to the rockwool cubes through the irrigation system. The key factor in managing the system is the management of the pH and EC (electrical conductivity) in the slab. Therefore samples of the nutrient solution from the slabs should be analysed periodically; at least once a month the nutrient solution should be analysed and, if necessary, the nutrient solution and frequency and time of irrigation adjusted.

Perlite

The use of perlite provides improved aeration and drainage and optimum moisture retention and nutrient availability. Perlite is not a trade name but the term used for naturally occurring siliceous volcanic mineral sieved and heated to 1000 °C. At these temperatures perlite expands to 4–20 times its original volume, due to the presence of 2–6 percent combined water in the perlite rock, producing a lightweight material with high porosity. Perlite can be used alone or mixed with other substrates for greenhouse plant production. It is a well-established substrate in Europe. The Mediterranean region has seen a rapid expansion of perlite soilless culture systems (growbags), pioneered by Spain, where they are used extensively, mainly for vegetable productions in the Almería and Murcia regions (Grillas *et al.*, 2001). There is a similar growth pattern (albeit on a smaller scale) observed in other parts of the Mediterranean, for example in Greece and North African countries. The high porosity helps to control the water-holding capacity and aeration of the substrate (Grillas *et al.*, 2001).

Vermiculite

Similarly to perlite, vermiculite is produced by heating the ground and sieved material to 700–1 000 °C. Vermiculite is sterile, light in weight and has a high TPS. Its volume weight is 0.1 g cm⁻³. Vermiculite is used as a sowing medium, covering germinating seeds, and as a component of potting soil mixtures. Media containing vermiculite should be mixed dry; when mixed wet, the desirable physical properties deteriorate because particles tend to collapse flat (Handreck and Black, 2005). While perlite is mainly used to improve the drainage properties in a mix, vermiculite is used to increase the water-holding capacity of a growing medium. It can hold 3–4 times its weight of water. Furthermore, vermiculite can hold positive-charged nutrients such as K, Mg and Ca.

Zeolite

Zeolites are silicate mineral with extremely high exchange capacities. The many different zeolites found around the world vary considerably in hardness and in the proportions of cations they contain (Handreck and Black, 2005). Zeolites possess a relatively high volume weight (1.9–2.3 g cm⁻³) and are therefore used in substrate mixtures; however, they are also used as single growing media. In a study with tomatoes, Savvas *et al.* (2004) reported highest yields when plants were grown in zeolite, followed by treatment involving zeolite in a substrate mixture.



GRUDA ET AL., 2006

Plate 3*Materials used as growing media*

From left to right and top to bottom: rockwool, polyurethane foam, expanded shale, volcanic material, open porous clay granulate, expanded clay, perlite, black peat, coarse wood fibre, fine wood fibre, vermiculite, and light peat

The good performance of the plants grown in zeolite was due to the considerable cation exchange capacity, enabling a more efficient buffering of excess ammonium and Mg concentrations in the root environment. Moreover, zeolite was capable of absorbing part of the excess Mg, resulting in more balanced macronutrient cation ratios in the root environment. On the other hand, during the initial wetting of the substrates with nutrient solution, most of the K was absorbed on the surface of the zeolite; as a result, the K concentration was sharply reduced in the solutions drained from substrates with constituents comprising zeolite. Using zeolite in sand mixtures offers potential in countries where sand is abundant (Al-Ajmi *et al.*, 2009). Zeolite has also been reported to protect plants against toxicity (e.g. from ammonium – Handreck and Black, 2005) or from heavy metals (Kapetanios and Loizidou, 1992).

Pumice

Pumice is a natural product, a light silicate mineral of volcanic origin. It is used as substrate for fruit vegetables (tomato, cucumber, pepper) and for cut flowers. There is increased interest in growing plants in pumice, because it requires relatively low

investments and is easily applicable in existing growing systems. Pumice can be used for many years, so it produces relatively little substrate waste. In addition, pumice is friendly to the environment, because no harmful production processes are involved (Boertje, 1995). Pumice is common in areas rich in volcanic activity, such as the Portuguese Azores, the Greek islands, Iceland, Japan, New Zealand, Russia, Sicily, Turkey and the United States (Raviv *et al.*, 2002). High transport costs limit its use in areas that do not have local deposits. Pumice has a low volume weight of $0.4\text{--}0.8\text{ g cm}^{-3}$ and a TPS of 70–85 percent (Boertje, 1995). Pumice has a neutral pH; it contributes little to plant nutrition, but does not decrease the availability of fertilizer nutrients (Handreck and Black, 2005).

Sand

Many grades of sand are available and can be used as a growing medium or as a component of various substrate mixtures in order to improve the drainage properties. Pure sand is widely used in deserts and coastal plains, because it is a cheap, local, natural source. The volume weight of sand is $1.48\text{--}1.80\text{ g cm}^{-3}$ and the TPS is relatively low at 0.30–0.45 (Raviv *et al.*, 2002). In Almería, beach sand is used as mulch on a stratified, artificial soil profile: manure is placed in strips, about 1 m wide and 2 cm deep, between the sand and the 20 cm of loam or clay soil placed on top of the original, rocky, sandy loam soil (Castilla *et al.*, 1986). According to the author, the use of sandy mulch soil in greenhouse crop production reduces loss through evaporation and allows the use of more saline water without reducing the harvest.

Tuff

Tuff is the common name for volcanic material used as a growing medium for greenhouse crops in several countries around the world. It has a TPS of 60–80% and a high surface area. The volume weight of tuff is $0.8\text{--}1.5\text{ g cm}^{-3}$. Rapid cooling of magma during eruption prevents the formation of primary minerals and, therefore, pyroclastic materials contain mainly vesicular, volcanic glass. The physical and chemical properties of tuff are determined mainly by its mineralogical composition and weathering stages, as well as the grinding and sieving processes (Raviv *et al.*, 2002). Tuffs possess a buffering capacity and may absorb or release nutrients, especially P, during the growth period (Raviv *et al.*, 2002).

Expanded clay granules

Expanded clay is a granular product with a cellular structure. It is produced by heating dry, heavy clay to $1100\text{ }^{\circ}\text{C}$: water is released, causing the clay to expand. The raw material must have a low content of soluble salts to avoid having to add substances, such as lime, during the process. Expanded clays are light with a low volume weight of $0.28\text{--}0.63\text{ g cm}^{-3}$; chemically, they are neutral, with a pH of about 7.0 (Raviv *et al.*, 2002). While expanded clays are used primarily for indoor plants in offices, they are also used for different greenhouse hydroponic cultures (Cervelli and Farina, 1994; Schnitzler *et al.*, 1994; Dobricevic *et al.*, 2008).

Organic growing media

The organic materials most available and applicable are peat, composts, bark and wood residues. However, availability alone is not sufficient: a substrate should be a standardized and growth-promoting product (Gruda, 2005). The organic substrates most used are described below.

Peat

Peat is the most widely used growing media and substrate component in horticulture, currently accounting for 77–80 percent of the growing media used annually in Europe's horticultural industry (Gruda, 2012a). Seedlings and transplants are grown predominantly in organic substrates based on peat (Plate 4); it is also used in horticulture as a raw material for substrates in which container plants are grown (Gruda, 2005). Peat has long been used as a component of standardized growing media; however, research in the 1960s showed that it could be used as a growing medium in its own right both for container plants and for vegetable and cut flower production (Puustjarvi, 1973). Peat substrates offer numerous advantages and their nutrient content and pH are easy to control because both are initially low.

Peat is formed as a result of the partial decomposition of sphagnum, other mosses and sedges. Under cool waterlogged conditions, sugar and celluloses decompose, leaving behind the lignified cell walls and humus. Different types of peat vary in their degree of decomposition (Handreck and Black, 2005). Plant species, climate and water quality all affect the distinct characteristics of peat (Raviv *et al.*, 2002).

Advantages of peat as a growing medium

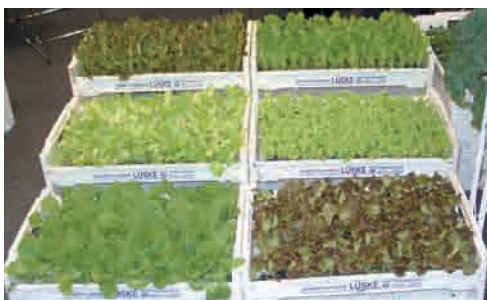
- Relative consistency
- Low nutrient content
- Low pH
- Light weight
- High volume of pores
- Good air capacity
- High water-holding capacity
- High CEC
- General freedom from pollutants, pathogens and seeds of weeds
- Stable structure
- Ease of storage
- Possibilities for reuse or recycling

Gruda, 2005; Gruda *et al.*, 2006



Plate 4

Peat-based growing media, used in press pot industry for production of lettuce seedlings



GRUDA, 2005

TABLE 2
Characteristics of different peats

Characteristics	Light peat	Dark peat	Black peat
Organic matter (% d.m.)	94–99	94–99	55–75
Ash (% d.m.)	1–6	1–6	23–30
Total porosity (% vol.)	84–97	88–93	55–83
Water-holding capacity (% vol.)	52–82	74–88	65–75
Volume weight (g/cc)	0.06–0.12	0.14–0.20	0.32–0.40
Cation exchange capacity (meq/100 g)	100–150	120–170	80–150
Total nitrogen (% d.m.)	0.5–2.5	0.5–2.5	1.5–3.5
C/N ratio	30–80	20–75	10–35
pH in water	3.0–4.0	3.0–5.0	5.5–7.3
Degree of decomposition ^a	H1–H3	H4–H6	H7–H10

^a According to Von Post (1937).
Gianquinto and Pimpini, 2001

Von Post (1937) suggested a classification of peat types, based on their degree of decomposition: light peat, dark peat and black peat (Table 2). The higher the degree of composition, the higher the pH value of the peat. For example, sphagnum peat has a very low degree of composition and an acidic pH of 3–4: it may be directly

applied to acid-loving plants; alternatively, the pH may be adjusted using dolomite lime. Peat is a very porous substrate with an excellent water-holding capacity; it is therefore used together with other growing media to increase the water mixture properties and reduce the weight of the mix for long distance transportation. Potential constraints are the instability, slumping and shrinkage of peat that can occur in container culture (Plate 5). Nevertheless, finding a replacement for peat as a horticultural substrate is an increasingly pressing issue.



Plate 5
Shrinkage of peat substrate in container

Peat-substitute growing media or alternatives to peat

The increased environmental awareness of consumers, the constant dismantling of ecologically important peat bog areas, and the pervasive waste problem all force the horticulture industry to re-examine its practices (Gruda, 2005; Gruda, 2012b). Numerous plant substrates have been introduced worldwide as peat substitutes or as peat-alternative growing media. Herein, only the most important substrates are presented, together with local materials used or suggested for use as growing media, such as composts of agro-industrial, animal and aquatic plant waste (Bragg, 1998), rice hulls (Evans and Gachukia, 2004 and 2008; Robbins and Evans, 2010) and peanut hulls (Bilderback *et al.*, 1982). Recently, biochar, a form of charcoal

manufactured from organic matter by heating in an anoxic situation (pyrolysis), has been used in agriculture and introduced into horticulture as a growing medium. Different materials, including coir, sawdust and woodchips, as well as cheap locally available sources, such as straw and organic waste can be used for its production.

Converting organic waste into biochar by heating organic material produces a standardized medium, with high stability, less volume weight, and good aeration and water-holding characteristics. Biochar can absorb phytotoxic compounds, is not easily available for micro-organisms, and has the advantage of being carbon neutral (Nichols and Savidov, 2010). Different experiments with different vegetables have been conducted, but to the authors' knowledge, biochar has not been commercially used in soilless Mediterranean greenhouses to date. Alternatives to peat used as growing media in the horticultural industry are described below.

Coir (coconut fibre)

Coir is used mainly in the greenhouse industry. The raw material, which looks like sphagnum peat but coarser, is derived from the husk of the coconut fruit commercially grown in, for example, Sri Lanka, India, the Philippines and Latin America.

Coir has good aeration and water-holding characteristics. Coir dust has a TPS (total pore space) of 86–94% and an AFP (air-filled pore space) of 9–14%, while coir fibre has a TPS of 98% and an AFP of around 70% (Raviv *et al.*, 2002). According to Prasad (1997a), coir dust is characterized by a relatively high EAW (easily available water) of around 35%. However, the water-buffering capacity is lower in coir than in peat, and the level of air space varies considerably depending on the origin of the material.

Leaching of nitrogen is marginally higher in coir than in peat when comparing materials of similar particle size. On the other hand, CO₂ evolution and stability indicate that coir is less stable than Irish peat (Prasad, 1997a) and the total water-holding capacity in coir waste is lower than in peat (Noguera *et al.*, 2000). Sometimes higher total soluble salts, sodium and chloride levels are found in coir: Noguera *et al.* (2000) investigated 13 coconut coir wastes commercially produced in six countries in Africa, America and Asia and found salinity varied between 0.4 and 6.0 dS m⁻¹. To be of good practical quality as a soilless culture substrate, coir has to be washed during production.

The typical pH range for coir is 5.5–6.8; it contains significant amounts of phosphorus (6–60 ppm) and potassium (170–600 ppm) (Robbins and Evans, 2010). A major advantage of coir is its relatively high elasticity and that it can be compressed in so-called coir briquets (Salvador *et al.*, 2005) which facilitate transportation from the country of origin. Since coir contains more lignin and less

cellulose than peat, it is more resistant to microbial breakdown and may shrink less; it is also easier to re-wet after drying than peat moss (Robbins and Evans, 2010).

Bark

Bark is a by-product of the wood and paper industry. It is usually stripped from trees, milled and screened into various sizes. As bark can be produced in different particle sizes, it is possible to make different mixes with different physical properties. Furthermore, according to Prasad and Chualáin (2004), the air- and water-holding capacity of bark can be adjusted by varying the percentage of fine material (< 1–2 mm). Bark is described as fresh, aged or composted (Robbins and Evans, 2010). Aged or composted bark is used for plant cultivation (Plate 6). Composting is recommended to eliminate phytotoxins. N may be added during composting to overcome N immobilization (Solbraa, 1979).

Bark is a lightweight material with a volume weight of 0.1–0.3 g cm⁻³ (Raviv *et al.* 2002). Pine-bark-based substrates provide very good aeration and a moderate amount of available water; however, they have little water-buffering capacity and frequent irrigation is required. Owen *et al.* (2008) suggested, therefore, amending bark substrate with industrial mineral aggregate following studies showing reduced water application needs and increased plant stomatal conductance and carbon assimilation when plants are grown in such substrates compared with in pine bark alone. Some fresh bark types contain toxins, including high levels of monoterpenes and phenols, which may prove harmful to plants. Tree species, age, harvest time, soil type and geographical region are factors affecting phytotoxicity (Raviv *et al.*, 2002). High manganese content, especially at low pH could also be a source of potential phytotoxicity (Maher and Thomson, 1991). As mentioned earlier, composting or ageing are good measures against phytotoxicity.

A positive property of bark is its relatively low cost. Shaw *et al.* (2007) performed a sensitivity analysis using five years of market data on ‘Galia’ muskmelons to show potential losses and profits using bags or pots filled with



Plate 6

Aged pine bark used as a container substrate for bell pepper cultivation

either perlite or pine bark. An economic analysis determined that pine bark was nearly one-eighth the cost of perlite and could be reused for several consecutive crops, resulting in reduced production costs and greater profits. However, bark could become a limited resource due to the changing timber industry and the fact that it is an effective energy source (Owen *et al.*, 2008).

Sawdust

The volume weight of sawdust is slightly less than sphagnum peat moss; it has similar water retention to pine bark but greater air space after drainage (Bilderback, 1982). As with hardwood bark, plant growth is restricted in uncomposted sawdust. However, the carbon to nitrogen ratio is much higher in sawdust than in bark and N must be added: an estimated 2–3 percent N by weight is required to compost sawdust. On the other hand, hardwood sawdust decays more rapidly than softwood sawdust and requires about 1 percent more N by weight to achieve decomposition (Worrall, 1985). Moreover, old sawdust has a lower N requirement than fresh sawdust. Handreck and Black (2005) reported rapid decomposition of whitewood sawdust in pots, with volume loss of up to 50 percent in one year, causing slumping and sometimes an enormous loss of air porosity. The microbes causing this decomposition have a high soluble nitrogen requirement, necessitating heavy applications of nitrogen fertilizer (Handreck and Black, 2005). Starck *et al.* (1991) found the lowest content of total and soluble nitrogen in leaves of carnation plants grown in sawdust in comparison to peat or mixtures of peat and sawdust. Higher doses of nitrogen increased the inflorescence diameter of plants grown in sawdust and in a mixture of 25 percent peat and 75 percent sawdust. In addition, using hardwood sawdust as a growing medium, it was found that wood contained phytotoxins negatively affecting plant growth (Maas and Adamson, 1982).

Woodchips and wood fibre substrates

Woodchips are readily available materials from the wood and paper industry. Pure untreated spruce and pine woodchippings with little bark from the woodworking industry can be shredded under frictional pressure and a wood fibre substrate (WFS) produced. The TPS of wood fibre substrates is similar to that of peat substrates and is over 90 percent, while the volume weight is generally 0.083–1.50, depending on the particle size and substrate compaction. The diminution of particle size leads to an increase in the volume weight (Gruda and Schnitzler, 2004a). Wood fibre substrates are characterized by low water retention with less easily available water and water-buffering capacity compared with peat-based substrates, good air content and high saturated hydraulic conductivity (Gruda and Schnitzler, 2004a; Gruda, 2005). Therefore, frequent irrigation is very important when wood fibres are used as growing media; optimal plant growth requires high moisture levels. Gruda and Schnitzler (2000) recommend irrigation set points at -30 hPa for optimal morphological leaf and root development of tomato transplants in an ebb/flood system; the irrigation frequency must be higher than in a peat-based substrate.

As with sawdust, the carbon to nitrogen ratio of woodchips and wood fibres is extremely high, requiring adequate amounts of nitrogen and composting to avoid negative effects on plant growth. In strongly fibrous and relatively loose wood substrates, micro-organism activity is sturdily promoted. The micro-organisms need mineral nitrogen for the synthesis of their own protein components. The immobilized N is no longer available for plants. N-immobilization in wood substrates can cause substantial nourishment problems for cultivated plants and thus become one of the most important factors leading to possible yield losses (Gruda and Schnitzler, 1997 and 1999b; Gruda *et al.*, 2000).

However, nowadays specially produced N-impregnated wood fibres can be used to reduce subsequent N-deficiency during the growing period. Gruda *et al.* (2000) studied the mechanism of N-immobilization for white peat and for WFSs with and without additional impregnation. Three levels of nitrogen fertilizer were tested. N-immobilization was calculated on the basis of N-balance including N-uptake by plants and residual mineral N in the substrates. Strong net N-immobilization was revealed in non-impregnated wood fibre substrates. In white peat and WFS *Toresa spezial*, N-immobilization was low with little variation in the values. N-immobilization for pots with and without plants was approximately 100 mg per litre for all three N-levels. The authors, therefore, recommended the use of N-impregnated wood fibre substrates with additional N-fertilization. However, general recommendations about additional fertilizer are difficult, given the strongly varying mineral nutrient content of different substrate loads.

Worldwide competition in the wood products industry also influences the prices of wood-based substrate; in recent years, the energy crisis has made the situation even more critical as wood is used as renewable fuel material. While the use of wood as an energy source is not a new phenomenon, the impact of its use as a biomass energy source has increased significantly in recent years.

Compost

The term compost is used to describe all organic matter that has undergone long, thermophilic, aerobic decomposition. Composts can vary according to the raw material used and the exact nature of the process (Raviv *et al.*, 2002). A wide range of organic waste can be composted for use as growing media: municipal solid waste, sewage sludge, poultry litter, chicken manure and other animal excreta, poppy straw, cotton gin trash, and waste from the food and processing industry. The latter includes apple pomace (Chong, 1992), corn cobs (Kianirad *et al.*, 2009), cotton gin waste (Krewer *et al.*, 2002), grape marc (Reis *et al.*, 2003), grape stalks (Tattini *et al.*, 1992), olive marc (Pages *et al.*, 1985), olive-mill waste (Papafotiou *et al.*, 2004 and 2005), sugarcane fibre or bagasse (Cintra *et al.*, 2004) and vegetable residues (Vallini *et al.*, 1992).

Prasad and Maher (2001) recommend using composted materials such as green waste and biowaste as a component of a growing medium (up to 50 percent) but not on their own. Constraints to the use of composted green waste are: high EC, high concentration of potassium, nitrogen and ammonium, and high shrinkage (Handreck and Black, 2005). Plant pathogens and weed contamination could also be potential problems if the temperatures and time exposure are insufficient and the composting process is not properly conducted (Gruda *et al.*, 2006). However, through a good composting process, compost generally possesses a suppressive effect against pathogens. Using compost provides alternatives in sustainable horticulture.

The physical and biochemical properties of compost used as growing media vary greatly, depending on the materials used, the method adopted and the stage of maturity. The most beneficial effect of compost inclusion in a growth medium is its nutritional contribution. Non-mature compost can immobilize a significant amount of N, but once stabilized, compost acts, to a large extent, as a slow-release fertilizer (Raviv *et al.*, 2002).

GROWING MEDIA REUSE

In soilless crops, the substrate is not renewed each year, but reused for successive growth cycles. Each time a soilless growing system is replanted, roots are left in the substrate and organic matter may be partially decomposed, increasing water-holding capacity and in some cases CEC.

Possible consequences of reuse are: variation in structure and composition, variation in the air-filled porosity and water-holding capacity ratio, and contamination by soil-borne diseases.

The international trend for substrate development tends towards the use of natural resources and renewable raw materials. When growing media companies, even peat producers, in the medium and long term actively participate in the search for peat alternatives and invest in new innovative technology, they will be investing in their future (Gruda, 2012a).

A high value in the future will be given to substrate development, assurance of quality of the final product, and the suitability for plant cultivation by simultaneously respecting environmental aspects and sustainability (Gruda, 2005).

TABLE 3
Volume weight, air at pF = 1 (% apparent volume), and easily available water (% apparent volume) for some new and reused substrates

	Reuse	Volume weight (g/cm ³)	Air (%)	EAW (%)
Coir	No	0.07	35.0	27.4
	Yes	0.09	24.4	30.3
Peat	No	0.13	44.8	24.1
	Yes	0.15	35.2	26.0
Sand	No	1.15	30.7	19.2
	Yes	1.16	13.4	34.4

Giuffrida *et al.*, 2001

GAP recommendations

- The wide range of substrates available means it is difficult to make a correct choice. For appropriate management of nutrient solution and fertigation, information concerning their chemical and physical characteristics is required; even within the same substrate, significant variations can occur:
 - Determine the substrate's physical and chemical characteristics and, if necessary, make adjustments to meet plant requirements.
- Shape and volume of the container affect water-holding capacity:
 - Consider the container when choosing a substrate.
- Choice of substrate depends on the grower's capability to handle growing media with characteristics that can greatly differ from those of agricultural soil:
 - Acquire the necessary information and know-how.
- Adapt the irrigation strategy to the physical properties of the substrate.
- The agro-economic suitability of a given substrate is not the sole consideration. The direct (i.e. substrate disposal) and indirect (i.e. leaching requirement) environmental impact must be taken into account in order to improve the efficiency *lato sensu* of the adopted soilless growing systems. Growing media companies and vegetable producers are no longer evaluated only according to their financial success:
 - Consider sustainability and environmental protection.
 - Adopt green technologies.

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12. Soilless culture

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TERMINOLOGY

Soilless culture can be defined as “any method of growing plants without the use of soil as a rooting medium, in which the inorganic nutrients absorbed by the roots are supplied via the irrigation water”. The fertilizers containing the nutrients to be supplied to the crop are dissolved in the appropriate concentration in the irrigation water and the resultant solution is referred to as “nutrient solution”.

In soilless crops, the plant roots may grow either in porous media (substrates), which are frequently irrigated with nutrient solution (see chapter 11), or directly in nutrient solution without any solid phase. In recent decades, supplying nutrient solution to plants to optimize crop nutrition (fertigation or liquid fertilization) has become routine cultural practice, not only in soilless culture but also in soil-grown greenhouse crops. Hence, the drastically restricted volume of the rooting medium and its uniformity are the only characteristics of soilless cultivated crops differentiating them from crops grown in the soil.

In recent years, cultivation in inorganic substrates has been characterized by a shift from open- to closed-cycle cultivation systems, involving reuse of drainage solution. The cultivation of greenhouse crops in closed hydroponic systems can substantially reduce the pollution of water resources by nitrates and phosphates stemming from fertigation effluents, and contribute to an appreciable reduction in water and fertilizer consumption (Savvas, 2002). Switching over to closed cultivation systems does not seem to restrict crop yield or product quality. However, a factor limiting the broad expansion of closed-cycle cultivation systems in substrate-grown crops is the accumulation of salt ions in the recycled nutrient solution. This phenomenon originates from the inlet of salt ions and water at higher ratios (concentrations in the irrigation water) than the corresponding ion-

to-water uptake ratios (Sonneveld, 2002). Furthermore, the reuse of the nutrient solution effluents in closed soilless culture systems is associated with the risk of disease spread via the recycled leachate, which entails the installation of a solution disinfection system (Wohanka, 2002).

The rapid expansion worldwide of hydroponic systems in the last three decades may be ascribed to their independence from the soil and its associated problems, i.e. the presence of soil-borne pathogens at the start of the crop and the decline of soil structure and fertility due to continual cultivation with the same or relative crop species. Soilless cultivation appears to be the safest and most effective alternative to soil disinfection by means of methyl bromide. It is therefore becoming increasingly important in protected cultivation – not only in modern, fully equipped glasshouses, but also in simple greenhouse constructions designed to optimize favourable climatic conditions. Hydroponic systems offer numerous advantages:

- Absence of soil-borne pathogens.
- Safe alternative to soil disinfection.
- Possibility to cultivate greenhouse crops and achieve high yields and good quality, even in saline or sodic soils, or in non-arable soils with poor structure (accounting for much of the world's cultivable land).
- Precise control of nutrition, particularly in crops grown on inert substrates or in pure nutrient solution (also in soilless crops grown in chemically active growing media, plant nutrition can be better controlled than in soil-grown crops, due to the limited media volume per plant and the homogeneous media constitution).
- Avoidance of soil tillage and preparation, thereby increasing crop length and total yield in greenhouses.
- Enhancement of early yield in crops planted during the cold season, because of higher temperatures in the root zone during the day.
- Respect for environmental policies (e.g. reduction of fertilizer application and restriction or elimination of nutrient leaching from greenhouses to the environment) – therefore, in many countries, the application of closed hydroponic systems in greenhouses is compulsory by legislation, particularly in environmentally protected areas, or those with limited water resources.

Despite the considerable advantages of commercial soilless culture, there are disadvantages limiting its expansion in some cases:

- High installation costs.
- Technical skills requirements.

Root aeration is a key factor for successful soilless cultivation. Understanding the factors influencing air availability in growing media is important for the successful management of substrate-grown crops. Oxygen deficiency may

readily occur in media with relatively low air-filled porosity, especially if the plants exhibit high growth rates and concomitantly intensive root respiration. When growing media characterized by low air-filled porosity are used, a good agricultural practice for avoiding aeration problems is to place the substrate in bags, containers or troughs in layers of at least 20 cm.

In countries where cultivation in greenhouses has reached industrial dimensions, these disadvantages are of minor importance. The average greenhouse size per enterprise is comparatively large and the investment costs per unit of greenhouse area high in order to maximize yield and optimize product quality by completely controlling all growing conditions. Therefore, the inclusion of equipment for hydroponics – a small aliquot of the total investment – constitutes the necessary supplement to exclude the last imponderable factor that could restrict yield and quality: the soil. Major greenhouse enterprises can afford the costs of specialized personnel or external advisory services and thus, the requirement for sufficient technical skills is not a problem. In contrast, when the greenhouse is a simple construction mainly based on favourable natural conditions (mild winter and increased solar irradiation), even a small increase in the installation and operation costs (as required for the introduction of hydroponics) may not be justifiable. The investment can be acceptable only when problems originating from the soil become critical, water resources are limited, or pollution of the environment by nutrient leaching is serious. The result is that commercial hydroponics is relatively limited in most Mediterranean countries.

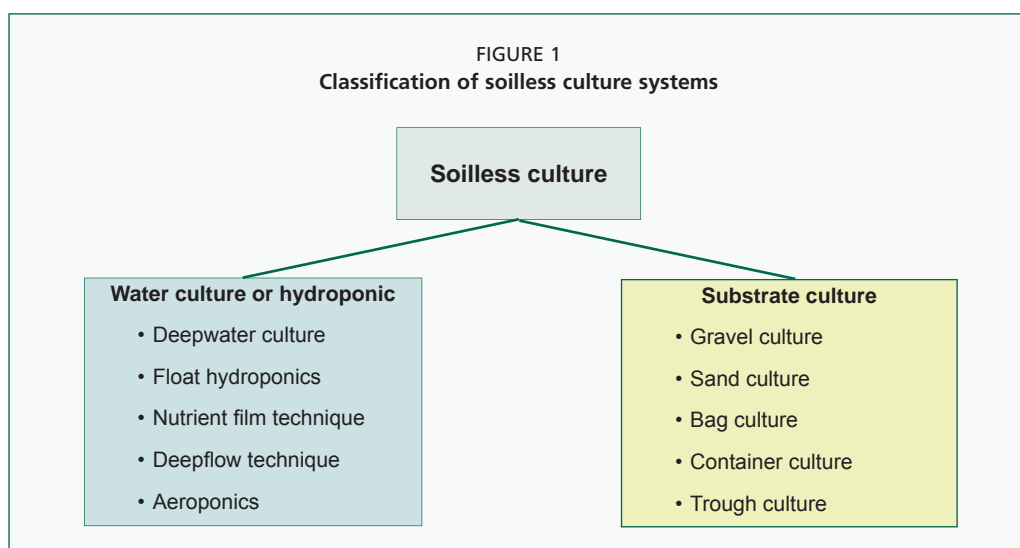
SYSTEMS AND EQUIPMENT

Intense research and experimental activities in soilless cultivation have led to the development of numerous systems characterized by different water volume, methods of water supply, nutrition management, size and shape of growing modules, and by the presence or absence of a variety of growing media (substrates).

Soilless cultures are usually classified according to the type of plant support as substrate culture (artificial, mineral or organic growing media, or a mixture of these) and water culture or hydroponic, where roots are partially or completely dipped in the nutrient solution (Figure 1).

For several reasons – differences in nutrient supply throughout the delivery system, varying plant growth and consequent differences in rate of nutrient uptake, and the quality of irrigation water (often scarce) – the supply of nutrients and water solution must exceed the crop's needs. Excess of nutrients and water assures that all plants are adequately fed, and leaching avoids excessive concentration of salts and non-essential elements (e.g. sodium) at root level. Soilless systems are also categorized in terms of management of the leachate (drained solution) as either open- or closed-loop systems.

FIGURE 1
Classification of soilless culture systems



Feeding plants in soilless systems

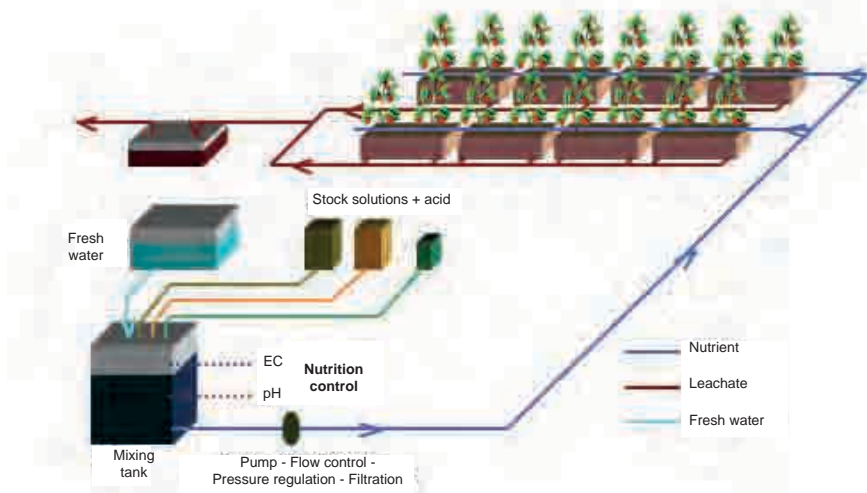
In all modern soilless systems, fertilization and irrigation are integrated into one system able to supply fertilizers and water at the same time (fertigation). Once it became evident that all nutrients essential for crops (macro- and micronutrients) could be supplied through hydrosoluble fertilizer salts, systems were developed with fertilizers dissolved at relatively high concentrations in special stock solutions. Stock solutions are injected and diluted in the irrigation water. Generally, two fertilizer tanks containing the stock solutions are used to separate fertilizers that can interact. A possible combination is a tank “A” containing essentially calcium fertilizers and a tank “B” with essentially phosphate and sulphate fertilizers. In this way, Ca is separated from P and $\text{SO}_4\text{-S}$ to avoid precipitation of calcium phosphate or calcium sulphate, which are sparingly soluble. A third tank “C” contains a concentrated solution of an inorganic acid which is used to control the pH of the nutrient solution obtained after the injection of the stock solutions into the irrigation water, and to wash the irrigation system and avoid clogging of the nutrient solution emitters.

Open- and closed-loop soilless systems

In open-loop systems the water and nutrients are supplied as for a conventional on-soil crop and the drained nutrient solution is thrown out of the system. The leachate may be collected and reused to fertilize on-soil crops, but in most cases it is lost causing harm to the environment (Figure 2). Open-loop systems determine the nutrient solution to supply in conjunction with leaching, i.e. the volumetric ratio of the leachate to the applied nutrient solution.

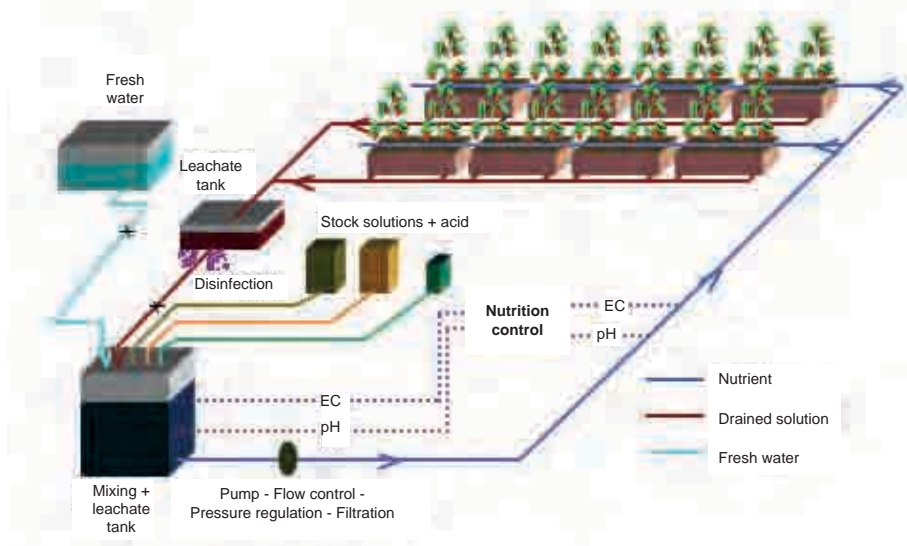
In closed-loop systems the drained nutrient solution is recovered, replenished and recycled (Figure 3). Compared with the open-loop system, it requires more

FIGURE 2
Open-loop soilless culture system



Standard Operational Practices, Ecponics

FIGURE 3
Closed-loop soilless culture system



Standard Operational Practices, Ecponics

precise and frequent control of the nutrient solution; technical know-how is needed, as it is more sensitive to operational mistakes, in particular during spring due to the possible increase of nutrient concentration in the solution with increasing temperature and solar radiation. The returned nutrient solution has to be treated to restore its original nutrient element composition and to remove any foreign substances. Moreover, spreading of root-borne diseases may occur, thus sterilization of the solution must be provided to kill pathogens.

Water culture or hydroponic systems

Deep water culture (DWC)

DWC, created in 1929 by Professor W.F. Gericke of the University of California, was the first hydroponic method proposed for commercial purposes. It consists of a bucket filled with nutrient solution, covered with a net and a cloth on which a thin layer of sand (1 cm) is placed to support the plants; the roots are suspended in the nutrient solution. Alternatively, the bucket may be covered with a lid and the plants, contained in net pots, suspended from the centre of the cover. The main drawback of the system is the hypoxic conditions occurring at root level, due to the limited air-water exchange area, compared with the volume of the solution, and the low diffusion coefficient of oxygen in the water. This constraint has been overcome by means of air pumps oxygenating the nutrient solution or by applying recirculating deep water culture systems (RDWC) that use a reservoir to provide nutrient solution to multiple buckets. In RDWC, as the water is reintroduced to the reservoir it is broken up and aerated with the use of spray nozzles.

Float hydroponics

Plants are grown on trays floating in tanks filled with nutrient solution. This method has a long history but its use in greenhouse production spread following the introduction of high density polystyrene or other “ultralight” plastic (e.g. Styrofoam) trays. It was used for the first time by Professor Franco Massantini at the University of Pisa, Italy, in 1976, to grow lettuce, cardoon and strawberry. Nowadays, the technique is principally adopted for the cultivation of fresh-cut leafy vegetables (lettuce, chicory, rocket, lamb’s lettuce etc.) and aromatics (basil, mint, thyme etc.).

The system appears to be particularly interesting due to the low set-up and management costs and the little automation required for monitoring and adjusting the nutrient solution. Classic FH systems are based on tanks 0.20–0.30 m deep, made of low-cost material (concrete, bricks, wooden planks) or directly dug into the greenhouse. Tanks are sealed (e.g. waterproofing with PE film) and filled with nutrient solution (150–250 litres m⁻²). The large volume of nutrient solution buffers the temperature and reduces the frequency of adjustment and reintegration of the solution. During the growing season, the O₂ concentration in the nutrient solution should range between 5 and 6 mg per litre. The easiest way to oxygenate



VENETO AGRICOLTURA

Plate 1

Baby leaf lettuce grown on multiple-tank system (left); basil grown on single-tank taking up the whole span (right)

the nutrient solution is by pumps that drive part of the solution into a pipe onto which a Venturi tube is inserted to insufflate air. However, the airflow should never become very strong, to avoid root damage and recirculation of plant exudates.

In the greenhouse, a single-tank or multiple-tank system may be used (Plate 1). The former, taking up almost the whole of the span, reduces the incidence of barren areas and allows the automation of certain operations, such as the placement and removal of floating trays; the latter consists of several tanks of $\geq 4 \text{ m}^2$ ($2 \times 2 \text{ m}$), with spacing of 0.5–1.0 m, and it reduces the risk of operational mistakes and diseases.

Nutrient film technique (NFT)

NFT is a hydroponic technique whereby a very thin layer (film) of nutrient solution flows through watertight channels (also known as gullies, troughs or gutters), wherein the bare roots of plants lie (Plate 2). Channels are on a slope of 1.2–3.0 percent and nutrient solution is applied at the elevated end so that the solution flows down through the channels keeping the roots completely wet. The slope may be provided by the floor itself, or benches or racks may hold the channels and provide the required elevation. The thin water stream (1–2 mm deep) ensures sufficient oxygenation of the roots, as the thick root mat which develops on the bottom of the channel has its upper surface continuously exposed to the air. At the lower end of the channels, the solution is drained to a large catchment pipe, which conducts the solution back to the cistern to be recirculated. Depressions in the channel floors must be avoided because ponds of immobile solution will lead to oxygen depletion and growth retardation.



D. SAVVAS

Plate 2

Nutrient Film Technique (NFT) – nutrient solution flows through the root system of tomato in a gully

Channels generally consist of various types of plastic material, such as polyethylene liner, polyvinylchloride (PVC) and polypropylene, with a rectangle- or triangle-shaped section. The base of the channel must be flat and not curved so as to maintain a shallow stream of liquid. Depending on the crop and the size of the channels, inlet flow rates vary between 1 and 3 litres per minute (2–9 litres m⁻² h⁻¹). Lower waterflow rates are recommended for crops such as lettuce, higher rates for fruiting vegetables. A distinction may also be made between the inflow rates needed for a young crop (e.g. 2–4 litres m⁻² h⁻¹) and a mature crop (e.g. 5–9 litres m⁻² h⁻¹).

Flow rates beyond this range are often associated either with oxygenation or nutritional problems: too rapid and the water becomes too deep and oxygenation of the roots inadequate; too slow and the result is lack of nutrients, especially for plants with roots downstream in the channel and exposed to water from which many other plants have already extracted nutrients, especially nitrogen and potassium. The rate of nutrient depletion along the channel also depends on length. As a rule, length should not exceed 12–16 m. In order to overcome these problems, a modified system called super nutrient film technique (SNFT) has been developed: nutrient solution is distributed by nozzles arranged along the channel, ensuring adequate availability of both nutrients and oxygen near the roots.

The delivery of nutrient solution may be continuous in a 24-hour cycle, or intermittent (alternating watering and dry periods to improve oxygenation of the root system). Another possibility – a compromise between these two approaches – is the continuous recirculation of the nutrient solution during daylight hours (dawn to dusk) and the automated switching off at night. Nevertheless, if recirculation of nutrient solution is intermittent, the volume capacity of the catchment tank has to be large enough to admit all the nutrient solution included in the system when recirculation is switched off. Before transplanting, the channels are usually covered with a black-on-white polyethylene film (0.15–0.25 mm thick), placing the film with the white side facing outwards (to reflect light and avoid excessive heating of the root and nutrient solution) and the black side inwards (to avoid light transmission and consequent development of algae). Plants destined for use in NFT systems are raised in small pots or plugs or in rockwool cubes and are placed in the channels when a substantial root system has formed.

The main advantages of NFT over other systems are the absence of substrate and the reduced volume of nutrient solution required, resulting in significant savings in water and fertilizers and reduced environmental impact and costs related to the disposal of the substrate. On the other hand, owing to the low water volume, the nutrient solution is subjected to major temperature changes along the channel and during growing seasons. Moreover, NFT has very little buffering against interruptions in water and nutrient supplies, and there is a considerable risk of the spread of root-borne diseases. Technically most crops could be grown

in a NFT system, but it works best for short-term crops (30–50 days), such as lettuce, because plants are ready to harvest before their root mass fills the channel.

Deep flow technique (DFT)

DFT is another method where roots are continuously exposed to moving water and nutrients. While with NFT, the water stream is as thin as possible, in DFT the continuously flowing nutrient solution has a depth of 50–150 mm. The large water volume simplifies the control of the nutrient solution and buffers the temperature, making the system suitable for regions where temperature fluctuation in the nutrient solution can be a problem. The width of the channels in a DFT system are usually about 1 m. Plants are grown on polystyrene trays which float on the water or rest on the channel sidewalls.

Aeroponics

Aeroponics is the growing of plants with the root system suspended in a fine mist of nutrient solution applied continuously or intermittently. Plants are secured in holes on polystyrene panels using polyurethane foam: panels are placed horizontally or on a slope, and fixed over a metal frame, arranging closed containers with a square or triangular section (Plate 3).

Water and nutrients are supplied by spraying the plant's dangling roots with an atomized nutrient solution by means of sprayers, misters or foggers inserted in PE or PVC pipes placed in the unit. The flow rate of the sprayers may range from 35 to 70 litres h⁻¹, whereas the spacing depends on the design and size of the cropping modules. As a general indication, they should be placed about 0.50 m apart to assure homogeneous nebulization all along the aeroponic unit. Spraying usually lasts 30–60 seconds, and their frequency varies according to species, plant growth stage, growing season and time of day (e.g. in summer, during rapid vegetative growth, a crop grown in northeast Italy may require up to 80 sprayings per day). At each nebulization, the drainage is collected at the bottom of the modules and recirculated.

Aeroponics permits a major reduction in water and fertilizer consumption and ensures adequate oxygenation of the roots. However, aeroponically grown plants may experience severe thermal stresses, especially in summer. Another disadvantage is the inability to buffer interruptions in the flow of nutrient solution (e.g. power outages). Aeroponics may be used for small-sized vegetables (e.g. lettuce and strawberries) and medicinal and aromatic plants.



Plate 3

Aeroponics: basil plants grown on polystyrene panels which are placed horizontally to form a square-frame system (left); lettuce plants grown on polystyrene panels placed on a slope to form an A-frame system (right)

Substrate culture

Substrate culture refers to soilless systems where a solid inorganic (sand, gravel, perlite, rockwool, volcanic stones etc.) or organic (peat, bark, coir, rice hulls etc.) medium offers support to the plants. Substrates retain nutrient solution reserves, thereby buffering interruptions in water and nutrient supply, and protect roots from temperature fluctuations. Cultivation on substrates is currently the primary soilless system used for the production of greenhouse peppers, cucumbers and tomatoes. Several substrates may be adopted as a growing medium in soilless cultivation and the choice is mainly based on water retention and water dynamics. Growing media for soilless systems are basically available as plastic encased slabs (e.g. rockwool, coir), prepacked substrate in plastic bags (e.g. perlite, peat, coir) or loose substrate granules placed directly in troughs, buckets or other containers made of strong and long-lasting plastic material.

Gravel culture

Gravel culture provides growing beds on a slope of 0.2–0.3 percent built either by digging the soil or as above-ground troughs. The beds are lined with thick plastic film (e.g. 0.5 mm black PE film) with a length of up to 30–40 m. In most gravel culture systems, subirrigation is applied. Alternatively, as in NFT systems, nutrient solution is applied at the high end, it flows down the trough and is drained at the lower end to be recovered and recirculated; this modified gravel culture system is known as the gravel film technique (GFT) (Plate 4).

The best choice of gravel for both subirrigation and GFT systems is particles of porphyry or granite of irregular shape and 3–20 mm diameter (> 50 percent of particles 10–15 mm diameter). The particles should not be of calcareous material in order to avoid pH alterations. If drip irrigation is used rather than subirrigation, smaller aggregates must be used (3–10 mm diameter; > 50 percent about 5 mm).



Plate 4

Gravel Film Technique (GFT) – porphyry beds

Sand culture

Plastic-lined beds are used (as for gravel culture) or sand is spread over the entire greenhouse floor. A drip irrigation system is used to feed each plant individually; waste nutrient solution is usually not recycled (open-loop system). A particular type of sand culture is *enarenado* (Plate 5): still widely used for greenhouse production in Almería, it was created to overcome the extremely poor indigenous soils in the region. *Enarenado* is prepared by levelling the soil and lining it with a layer of



G. GIANQUINTO

Plate 5

Cucumbers (top); beans (middle) grown on enarenado in Almería, Spain; close-up of soil on which the plants are grown (bottom)



G. GIANQUINTO AND VENETO AGRICOLTURA

Plate 6

Strawberry grown on perlite bags (top); pepper grown on coir slabs (middle); tomato grown on rockwool slabs (bottom)

compacted clay (about 20 cm), followed by a layer of 2–3 cm of fermented manure or organic material (composted crop residues). A layer of 10 cm of washed beach sand or coarse grit finally sits on the bed. The clay layer has a double function: preventing water leaking into the ground; stopping capillary rise from the saline watertable.

Bag culture

Bag culture is the cultivation of plants on plastic bags filled with either porous slabs or loose granules (Plate 6). The substrate-filled bags may be manufactured and purchased as ready-to-use bags or filled by the grower.

Slab-type growing media are either rockwool or coir; rockwool slabs are usually about 90 cm long, 8–10 cm high and 15–20 cm wide. The 15-cm-wide slabs are best suited for growing plants like pepper and tomato. The wider slabs are for crops such as cucumbers that require a strong and stable base and a large root capacity. Coir slabs expand their size after rehydration, reaching 90–110 cm in length, 15–20 cm in width and 6–12 cm in height.

**Plate 7**

Holes on the top of bags/slabs for planting (top); saturation of bags with nutrient solution before transplanting (bottom)

**Plate 8**

After saturating the substrate, vertical slits (top) or “L-shaped” slits (bottom) are incised at the basal edge of the bag, midway between two plants; each arm of the “L” is 2–3 cm long

**Plate 9**

Tomato transplants rooted in rockwool cubes, ready to be planted

Bag culture

Advantages:

- Less substrate volume use
- Bags can be removed easily if there is any infection
- Simplicity

Disadvantages:

- Needs labour to fill (if ready-for-use bags not available at the market)

The granulated materials most widely used in Mediterranean countries as substrates in bag culture are perlite, peat, coir, pumice or a mixture. Bags are placed in channels or panels to collect the drainage solution. Planting holes are cut in the top (Plate 7); the number of planting holes varies depending on the crop, but as a guide, 3–5 tomatoes can be planted into a slab or bag 90–100 cm long and 15–20 cm wide. As soon as planting holes are ready, one dripper per hole is put in position, and the substrate is saturated with nutrient solution. Saturation is maintained for 24–48 hours to allow the substrate to absorb the solution. Small holes or cuts are made along the base of the plastic envelope to allow excess nutrient solution to drain (Plate 8). Saturation serves to extract the air and provide homogeneous wetting of the growing medium, providing adequate water and nutrient reserves and optimal EC and pH conditions in the plant root zone, and diluting accumulated salts (in the case of substrate reuse).

Transplants rooted in rockwool cubes or similar media are planted when the roots are about to emerge from the base of the cube (Plate 9). The nutrient solution or water

is delivered via a drip irrigation system (1 or 2 drippers per plant, dripper capacity of 2–4 litres h⁻¹). The nutrient solution may be recycled or not, but in open-loop systems an environmentally acceptable means of disposal of the effluent from the substrate is required. Slabs and bags can be reused several times and then they must be discarded.

Container culture

Different containers – PE, PVC or polystyrene buckets or pots (Plate 10) – are used. The volume of the containers varies from 12 to 18 litres and 1–2 plants per container are usually planted. The container depth is important for adequate root development and plant growth, and the deeper the container the higher the ratio of air to water in the substrate. The container depth depends on crop, length of growing season and type of substrate. In general, a depth of > 20 cm is required. A drip irrigation system is used to feed each plant individually and drainage is usually ensured by an overflow opening in the base of the container. The growing media most commonly used in container culture are peat and coir (plain or mixed with perlite, pumice, lapilli or zeolite) and perlite. The same general operating procedures are used as with bag culture.

Trough culture

Plants grow on plastic or plastic-lined troughs built above ground (Plates 11 and 12). Trough depth varies from 10 to 35 cm depending on the substrate and particle size (0.3–0.5 mm particles require a depth of at least 35 cm). Troughs should have a uniform slope of 0.5 percent. A drain pipe with a diameter of at least 30 mm is placed on the bottom of the trough from one end to the other. Plants are spaced

Container culture

Advantages:

- Low substrate volume
- Containers are easily removed if there is any infection
- Simplicity

Disadvantages:

- Needs labour to fill
- Cost of container



G. GIANQUINTO



Plate 10

Tomatoes grown on polystyrene buckets filled with coir in Morocco (above), and on PE cases filled with perlite in Turkey (below)



G. GIANQUINTO

Plate 11

Tomatoes grown in plastic-lined troughs filled with coir



G. GIANQUINTO

Plate 12

Tomatoes grown in plastic-lined troughs built above-ground and filled with coir, Morocco

Trough culture

Advantages:

- Easily adapted to small scale farmers' conditions since similar to soil
- Any problems in the individual drippers could be tolerated
- Suitable for crops with high plant density (e.g. lettuce)

Disadvantages:

- Needs labour to fill and change substrate
- Substrate volume per plant is generally higher

normally and drip irrigation feeds each plant individually. The growing media used in trough culture and the general operating procedures are the same as those applied in container culture.

Greenhouse layout and equipment

As a rule, in soilless culture the soil is covered with black-on-white polyethylene film (0.20–0.25 mm thick). The film is placed with the white side facing up to maximize reflection, improve brightness at plant level and minimize the trapping of excess heat inside the greenhouse. The black side faces downwards to control weeds. Mulching reduces the relative humidity of the air, eliminating evaporation from the soil and preventing contact between plants and soil, thus reducing the risk of disease.

Soilless culture (except DWC and FH) requires fertigation systems: to mix appropriately water and fertilizers dissolved in concentrated stock solutions; and to uniformly supply feed solution to every plant. Fertigation equipment typically comprises the following:

- Pressure regulators to reduce incoming water pressure to a set pressure suitable for the delivery system.
- Filters (typically 80 micron or 200 mesh) to protect from blockages caused by water impurity or precipitated salts.
- Tanks for stock and for acid solution, made of inert materials resistant to acids and salts (usually polypropylene or PVC) and typically $\geq 1\,000$ -litre volume for chemical storage between injection times.

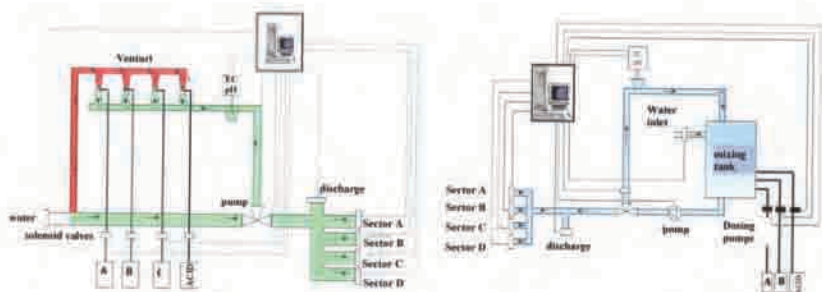
- Fertilizer injection devices to take a small amount of stock solution and introduce it into the waterline for delivery to plants.
- pH and EC measuring tools – the pH (acidity or alkalinity) and electrical conductivity (EC) of water and nutrient solution are measured using pH meters and EC meters, respectively.
- Water/solution delivering system – the equipment used to supply nutrient solution in liquid hydroponic systems is illustrated above; in substrate-grown soilless crops, nutrient solution is delivered via a drip irrigation system with microtubes (commonly known as spaghetti tubes) as emitters.

The injection of stock solution in the irrigation pipe (Figure 4, left) is inappropriate with high bicarbonate concentration in the water; the pressure caused by the formation of CO_2 owing to the acid-bicarbonate reaction does not allow completion of the reaction itself. Thus as the water pressure inside the line decreases (e.g. at emitter level), the acid-bicarbonate reaction stops and the solution pH increases. Injection of stock solutions into a mixing tank (Figure 4, right) ensures that all water enters into an open tank where stock and acid solutions are injected on the basis of continuously monitored EC and pH values; the feed solution is then injected into the main pipe. This system has advantages:

- The EC and pH values of the solution are fairly constant.
- The solution remains in the mixing tank for a sufficiently long time to allow for a complete reaction between acid and bicarbonate.
- An open tank allows the removal of CO_2 from the solution, thus speeding up the acid-bicarbonate reaction.

The result is better pH regulation; injection into a mixing tank is the most appropriate technology for closed-loop soilless systems with nutrient solution recirculation.

FIGURE 4
Proportional injectors dispensing the stock solutions either directly in the irrigation pipe (left) or in a mixing tank (right)



Note that fertilizer injection devices can be classified into volumetric (or quantitative) and proportional injectors:

Volumetric injectors are relatively easy-to-use and their cost is low but they are affected by water pressure changes and cannot adjust fertilizer concentration to EC or pH fluctuations occurring in the water. The simplest volumetric injector is based on Venturi devices that reduce pressure (vacuum), sucking the fertilizer solution into the line. With other devices (e.g. Dosatron), the amount of stock solution is directly proportional to the volume of water entering the injector, irrespective of variations in waterflow or pressure which may occur in the main waterline. Volumetric dosage can also be performed by electric pumps, but in this case the cost increases.



D. SALINAS

Plate 13

Venturi device as part of a simple volumetric injector used to prepare nutrient solution by diluting stock solutions with water



VENETO AGRICOLTURA

Plate 14

Open mixing tank that allows completion of the acid/bicarbonate reaction

Proportional injectors include electric pumps (diaphragm or piston) able to dispense stock solutions either into the waterline or into a mixing tank, depending on the EC or pH value detected downstream. The main advantages of these devices are: accuracy in obtaining a solution with fixed pH and EC – so they are suitable for water characterized by variations in chemical composition and for closed-loop soilless systems; and automation easy to apply. Their main drawback is the high cost and maintenance requirement.

CROP NUTRITION IN SOILLESS CULTURE

Principles

In soilless culture, all essential plant nutrients should be supplied via the nutrient solution, with the exception of carbon, taken up from the air as CO_2 . To prepare nutrient solutions containing all essential nutrients, inorganic fertilizers are used as nutrient sources, except for iron, which is added in chelated form to improve its availability for the plants. Most fertilizers used to prepare nutrient solutions in soilless culture are highly soluble inorganic salts but some inorganic acids are also used. A brief description of the water soluble fertilizers commonly used in soilless culture is given in Table 1.

TABLE 1
Water soluble fertilizers commonly used in soilless culture

Fertilizer	Chemical formula	Percentage in nutrient	Molecular weight (g)	Solubility (kg litre ⁻¹ , 0 °C)
Ammonium nitrate	NH ₄ NO ₃	N: 35	80.0	1.18
Calcium nitrate	5[Ca(NO ₃) ₂ ·2H ₂ O] NH ₄ NO ₃	N: 15.5, Ca: 19	1 080.5	1.02
Potassium nitrate	KNO ₃	N: 13, K: 38	101.1	0.13
Magnesium nitrate	Mg(NO ₃) ₂ ·6H ₂ O	N: 11, Mg: 9	256.3	2.79 (20 °C)
Nitric acid	HNO ₃	N: 22	63.0	-
Monoammonium phosphate	NH ₄ H ₂ PO ₄	N: 12, P: 27	115.0	0.23
Monopotassium phosphate	KH ₂ PO ₄	P: 23, K: 28	136.1	1.67
Phosphoric acid	H ₃ PO ₄	P: 32	98.0	-
Potassium sulphate	K ₂ SO ₄	K: 45, S: 18	174.3	0.12
Magnesium sulphate	MgSO ₄ ·7H ₂ O	Mg: 9.7, S: 13	246.3	0.26
Potassium bicarbonate	KHCO ₃	K: 39	100.1	1.12
Iron chelates	various types	Fe: 6–13	-	-
Manganese sulphate	MnSO ₄ ·H ₂ O	Mn: 32	169.0	1.05
Zinc sulphate	ZnSO ₄ ·7H ₂ O	Zn: 23	287.5	0.62
Copper sulphate	CuSO ₄ ·5H ₂ O	Cu: 25	249.7	0.32
Borax	Na ₂ B ₄ O ₇ ·10H ₂ O	B: 11	381.2	0.016
Boric acid	H ₃ BO ₃	B: 17.5	61.8	0.050
Sodium octaborate	Na ₂ B ₈ O ₁₃ ·4H ₂ O	B: 20.5	412.4	0.045
Ammonium heptamolybdate	(NH ₄) ₆ Mo ₇ O ₂₄	Mo: 58	1 163.3	0.43
Sodium molybdate	Na ₂ MoO ₄ ·2H ₂ O	Mo: 40	241.9	0.56

In commercial soilless culture, the fertilizers needed to prepare a nutrient solution are mixed with water to form concentrated stock solutions, which are then automatically mixed with irrigation water to form nutrient solution.

Composition of nutrient solution

To formulate the composition of a nutrient solution for a certain crop, experimental results concerning the nutritional requirements of the particular plant species should be available. Such data are also essential to check and adjust the nutritional status in the root zone during the cropping period. The composition of nutrient solutions and the optimization of nutrition in commercial hydroponics have been primary objectives of research related to soilless culture in recent decades. The pioneer work on the composition of nutrient solutions was carried out by American scientists before the Second World War and resulted in the formula of Hoagland and Arnon (1950), widely used for research purposes even today. This formula is presented in Table 2.

TABLE 2
Composition of standard nutrient solutions

Macronutrient	H&A	S&S (cucumber)	S&S (tomato)	Micronutrient	H&A	S&S (cucumber)	S&S (tomato)
	mmol per litre				μmol per litre		
NO ₃ ⁻	14.0	16.00	17.00	Fe	25.00	15.00	10.00
H ₂ PO ₄ ⁻	1.0	1.25	1.50	Mn	9.10	10.00	10.00
SO ₄ ²⁻	2.0	1.375	2.50	Zn	0.75	5.00	4.00
K ⁺	6.0	8.00	8.00	Cu	0.30	0.75	0.75
NH ₄ ⁺	1.0	1.25	1.00	B	46.30	25.00	20.00
Ca ²⁺	4.0	4.00	5.25	Mo	0.10	0.50	0.50
Mg ²⁺	2.0	1.375	2.00				

H&A: As proposed by Hoagland and Arnon (1950) for universal use.
S&S: As proposed by Sonneveld and Straver (1994) for commercial cultivation of cucumber and tomato in rockwool.

After the Second World War, efforts focused on adapting the basic formula of Hoagland and Arnon (1950) to the needs of individual crop species. With the support of new developments in analytical techniques and equipment, specific nutrient solutions were formulated for each greenhouse crop species. Such formulae have been published by Sonneveld and Straver (1994), Resh (1997), De Kreij *et al.* (1999), Papadopoulos (1991 and 1994), Adams (2002) etc. Two examples of formulae suggested by Sonneveld and Straver (1994) for cucumber and tomato are given in Table 2.

In commercial practice, it is not easy to implement nutrient solution formulae like those given in Table 2. The first difficulty arises from the mineral composition of the irrigation water. In most cases, irrigation water contains macronutrients (Ca²⁺, Mg²⁺, SO₄²⁻), micronutrients (Mn²⁺, Zn²⁺, Cu²⁺, B and Cl⁻) and other non-nutrient ions (HCO₃⁻, Na⁺) at appreciably high concentrations. When the concentration of a nutrient element in the irrigation water represents a non-negligible fraction of the target concentration in the nutrient solution, the grower has to deduct the amount that is already available in the irrigation water from the total required amount in the nutrient solution. The concentration of bicarbonates (HCO₃⁻) in the irrigation water is also very important since it determines the amount of acid required for pH adjustment. Furthermore, the concentration of Na⁺ has to be taken into consideration, since it determines the ultimate EC of the nutrient solution supplied to the crop. However, since the concentrations of all these nutrient and non-nutrient ions are different in the irrigation water used by each individual grower, the amount of fertilizer required to prepare a nutrient solution with a standard composition differs from grower to grower. Thus, the calculations have to be performed individually for each grower. A further difficulty is the inability to supply a certain amount of a macronutrient independently of the supply of the other macronutrients, due to the lack of single-nutrient fertilizers (with the exception of N). For example, soluble potassium (K⁺) can be added either as KOH or as a salt (KCl, KNO₃, KH₂PO₄, K₂SO₄ etc.) to an

aqueous solution. However, the supply of K in the form of KOH is accompanied by the concomitant supply of OH⁻ ions which raise the pH of the solution to harmful levels for the plants. Similarly, the supply of potassium salts results in the concomitant supply of another element in the form of an anion at a fixed molar ratio depending on the valence of this anion (normally either 1:1 or 2:1).

To overcome these complications and avoid laborious repetition, special computer programs have been developed for the calculation of the amounts of individual fertilizers required to prepare a nutrient solution with a given composition using irrigation water. Savvas and Adamidis (1999) have proposed a simple program that can be easily applied to calculate the amount of fertilizer needed to prepare commercial nutrient solutions when a target composition is available and the mineral composition of the irrigation water is known. This program, which operates via a Microsoft EXCEL[®] platform, is freely accessed via the Internet at: www.ekk.aua.gr/excel/index_en.htm.

To calculate the amount of fertilizer needed to prepare a nutrient solution using a computer program, it is necessary to introduce input data describing its composition. When using a program based on the algorithm proposed by Savvas and Adamidis (1999), the composition of the nutrient solution has to be defined by selecting target values for the following solution characteristics:

- Electrical conductivity (EC) in dS m⁻¹ – a measure of the total salt concentration in the nutrient solution
- pH
- Levels of K, Ca and Mg, which can be alternatively introduced either as mutual ratios (K:Ca:Mg on a molar basis, denoted by X:Y:Z) or as fixed concentrations (mmol litre⁻¹)
- Level of N, which can be defined by specifying one of the following:
 - a total nitrogen to potassium ratio (total-N/K denoted by *R*) in combination with an ammonium to total nitrogen ratio (NH₄-N/total-N denoted by *N_r*), both on a molar basis
 - a total nitrogen to potassium ratio (total-N/K on a molar basis, denoted by *R*) in combination with a fixed NH₄-N concentration (mmol litre⁻¹)
 - a fixed NO₃-N concentration (mmol litre⁻¹) in combination with an ammonium to total nitrogen ratio (NH₄-N/total-N on a molar basis, denoted by *N_r*); or
 - a fixed NO₃-N concentration (mmol litre⁻¹) in combination with a fixed NH₄-N concentration (mmol litre⁻¹)
- Concentration of H₂PO₄⁻ (mmol litre⁻¹)
- Concentrations of micronutrients (μmol litre⁻¹), specifically Fe, Mn, Zn, Cu, B and Mo

If the desired composition of a nutrient solution is given in terms of fixed target concentrations, the EC of this solution is also fixed and can be calculated using the following relationship established by Savvas and Adamidis (1999):

$$C = 9.819E - 1.462 \quad \text{Eq. 1}$$

where:

E depicts the EC (dS m^{-1})

C depicts the sum of the cation concentrations (meq litre^{-1}) in the nutrient solution, including also non-nutrient macrocations, particularly the Na^+ concentration

Consequently, when only macronutrient concentrations but no macronutrient ratios are given to define the desired nutrient solution composition, it is meaningless to select a target EC, since only one fixed EC, specifically that calculated by Equation 1, is feasible. In contrast, if the desired composition of the nutrient solution is defined by selecting target macronutrient ratios, it is possible to select any desired EC.

To calculate the amount of fertilizer needed to prepare a nutrient solution, it is important to introduce also the following information to the computer program, in addition to the data describing the desired composition:

- EC, pH and concentrations of nutrients (K, Ca, Mg, $\text{NO}_3\text{-N}$, $\text{SO}_4\text{-S}$, Mn, Zn, Cu, B, Cl) and non-nutrient ions (Na^+ and HCO_3^-) in the irrigation water used to prepare the nutrient solution
- Percentage of Fe in the Fe-chelate used as iron source
- Available source of soluble P (KH_2PO_4 or H_3PO_4) and percentage of pure H_3PO_4 in the commercial-grade H_3PO_4 , if the latter is used as P fertilizer (commonly 85%)
- Percentage of pure HNO_3 in the commercial-grade HNO_3 , if the latter is used for pH adjustment when preparing the nutrient solution
- Available source of B (see Table 1)
- Available source of Mo (see Table 1)
- Volume of stock solutions (m^3)
- Desired concentration factor, defined for a particular fertilizer as the ratio of its concentrations in the stock solution and the solution supplied to the crop (commonly 100, dictated by the least solubility of the fertilizers used)

The output obtained by implementing a computer program to calculate a nutrient solution comprises the weight of fertilizer (kg for macronutrients, g for micronutrients) to be added in the two-stock solution tanks (A and B) for the given volume. If the target nutrient solution composition introduced as input data includes macronutrient concentrations and not ratios, the computer program

also calculates the target EC. The target values of EC and pH are subsequently introduced to the controlling system of the fertigation head used to automatically prepare fresh nutrient solution by diluting the stock solutions.

As a rule, the fertilizer used as a source of calcium is calcium nitrate, because calcium phosphates and sulphates are sparingly soluble fertilizers, and calcium chloride would result in the addition of chlorides at undesirable concentrations. Magnesium and sulphates are added in the form of magnesium sulphate. If the target concentration of magnesium is higher than that of sulphate, the extra Mg is added in the form of magnesium nitrate. However, if the target concentration of sulphate is higher than that of magnesium, extra SO_4^{2-} is needed, added in the form of potassium sulphate. Phosphorus is added as monopotassium phosphate but can alternatively be added as phosphoric acid, depending on the concentration of bicarbonates in the irrigation water. Ammonium is commonly added as ammonium nitrate. Potassium is primarily added as potassium nitrate but, to compute the amount to be added, the concentration of K originating from the addition of potassium sulphate and monopotassium phosphate is deducted from the target K concentration. Nitrate-N is added in the form of calcium nitrate, magnesium nitrate, potassium nitrate, ammonium nitrate and nitric acid. The allocation of the required $\text{NO}_3\text{-N}$ to the above referenced $\text{NO}_3\text{-N}$ fertilizers depends on the target concentrations of Ca, Mg, K, SO_4^{2-} , H_2PO_4^- in the nutrient solution and the concentration of bicarbonates in the irrigation water.

The concentration of HCO_3^- in the irrigation water dictates the amount of HNO_3 to be added to control pH but has an impact also on the addition of H_3PO_4 . When preparing fresh nutrient solution by diluting stock solutions with irrigation water, the adjustment of the target pH entails the conversion of the bicarbonates contained in the irrigation water to CO_2 (Savvas and Adamidis, 1999). This reaction requires the addition of acid at an $\text{H}^+ : \text{HCO}_3^-$ molar ratio of 1 : 1. The target P concentration in nutrient solutions rarely exceeds 1.5 mmol per litre. Hence, it is not possible to add more phosphoric acid than that resulting in a P concentration of 1.5 mmol per litre in the nutrient solution. However, the bicarbonate concentrations in most sources of irrigation water in Mediterranean countries are much higher than 1.5 mmol per litre. If the concentration of bicarbonates in the irrigation water is about 0.5–1.0 mM higher than the target P concentration in the nutrient solution, nitric acid has to be used to adjust the target pH, either in addition to phosphoric acid, or as a sole source of H^+ . High HCO_3^- concentrations in the irrigation water are essentially accompanied by equally high concentrations of cations, particularly Ca^{2+} and Mg^{2+} . Thus, when preparing a nutrient solution using tap water with a high HCO_3^- concentration, an increased addition of NO_3^- in the form of HNO_3 in order to control pH is compensated for by a decreased supply of NO_3^- in the form of $\text{Ca}(\text{NO}_3)_2$. If a high HCO_3^- concentration in the tap water is accompanied also by a high Mg^{2+} concentration, less Mg^{2+} is added in the form of MgSO_4 . Then, the necessary SO_4^{2-} is added in the form of K_2SO_4 , resulting in reduced addition

of NO_3^- in the form of KNO_3 . Consequently, even if the HCO_3^- concentration in the tap water is high, there is no risk of adding too much NO_3^- to the nutrient solution when HNO_3 is used to adjust the pH.

Regarding metallic micronutrients, iron is added as chelated Fe, while Mn, Zn and Cu are added in the form of their sulphate salts. The commonly used B fertilizers in soilless culture are sodium tetraborate, sodium octaborate and borax, while the commonly used Mo fertilizers are sodium molybdate and ammonium hepta-molybdate. The selection of the B or Mo fertilizer depends on current availability or market prices and not on the addition of other nutrients or the composition of the irrigation water.

An interesting aspect related to the nutrition of soilless-grown plants in greenhouses, which has received attention during the last two decades, is the inclusion of silicon in the nutrient solution. Silicon improves the growth of plants subjected to both abiotic and biotic stress conditions when supplied via the nutrient solution in hydroponics, although it seems to have no effect under non-stress conditions. Silicon is added to the nutrient solution in the form of liquid potassium silicate ($\text{SiO}_2 \cdot 2\text{KOH}$), which has a strong alkaline reaction and should, therefore, be supplied to the plants from a separate stock solution tank. The high alkalinity of potassium silicate is controlled by enhancing the HNO_3 injection dosage during the process of nutrient solution preparation. The extra supply of nitrogen in the form of HNO_3 and K in the form of $\text{SiO}_2 \cdot 2\text{KOH}$ to the nutrient solution is compensated for by a corresponding reduction in KNO_3 injection.

Impact of nutrition on yield

The EC is considered to be one of the most important properties of the nutrient solutions used in soilless culture. If the EC of a nutrient solution is too low, the supply of some nutrients to the crop may be inadequate. Similarly, when the EC is too high, the plants are exposed to salinity. However, the yield response of the plants to the EC of the nutrient solution may vary widely among different species. Therefore, for each cultivated plant species, the terms “too low” and “too high” need to be quantitatively defined based on experimental results.

In semi-arid regions such as those in the Mediterranean Basin, the presence of NaCl at relatively high concentrations in the available irrigation water is a common condition. When such irrigation water is used to prepare nutrient solutions, the concentration of NaCl is added to that of nutrients and thus the EC in the resultant nutrient solution is correspondingly increased. Furthermore, in the Mediterranean region, Ca and Mg may also occur at higher concentrations in the irrigation water than the target concentrations in the nutrient solutions. In such cases, the target Ca and Mg concentrations in the nutrient solution are essentially as high as in the irrigation water and thus higher than the desired level, thereby resulting in a correspondingly higher EC than the target EC level.

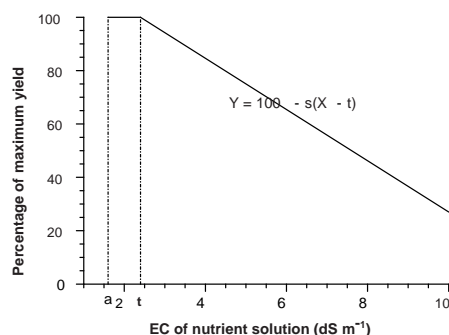
Some growers in the Netherlands and other parts of the world apply desalination by means of reverse osmosis in order to deal with the problem of high salt concentrations in the irrigation water. However, desalination technologies incur high production costs for growers and are affordable only in high-technology greenhouses used for high-value crops.

The growth and yield responses of hydroponically grown plants to the total salt concentration in the nutrient solution may be described by the generalized model presented in Figure 5. According to this model, if the EC is lower than a particular value (a), an increase in the EC to values not exceeding (a) enhances the yield of the crop. If the EC ranges between (a) and (t), where (t) is the upper critical EC level, known as salinity threshold value (STV), the yield of the crop remains constant. However, any further increase in the EC above (t) results in yield decrease. If all nutrients are included at sufficient levels in the nutrient solution, the decreases in growth and yield follow a linear pattern as the EC increases to higher levels than (t). The rate of yield decrease per unit increase of EC is termed salinity yield decrease (SYD). The impact of the increased EC on plant growth in hydroponics depends also on the prevailing climatic conditions. As a rule, the detrimental salinity effects are more pronounced under high light intensity and low air humidity.

The optimal pH in the root zone of most crop species grown hydroponically ranges from 5.5 to 6.5, although values between 5.0–5.5 and 6.5–7.0 may not cause problems in most crops (Adams, 2002). However, in soilless culture, when maintaining marginal values of the optimum pH range, the risk of exceeding or dropping below them for some time increases due to the limited volume of nutrient solution per plant that is available in the root zone. Most plants, when exposed to external pH levels > 7 or < 5 , show growth restrictions (Sonneveld, 2002). Nevertheless, there are also plant species, such as gerbera and cut chrysanthemums, which perform better at low pH due to the higher susceptibility of these species to chlorosis induced by Fe, Mn, Zn and Cu deficiencies.

Overall, values of pH above 7.0 in the root zone of soilless cultivated plants can quickly result in the appearance of P-, Fe- and Mn-, but sometimes also in Cu- and Zn-deficiency symptoms. The appearance of P-deficiency at pH values

FIGURE 5
Relationship between the relative yield (% of the maximum yield) in soilless-grown tomato crops and the electrical conductivity (EC) of the nutrient solution in the root zone



Maximum yield is that obtained when $a \leq EC \leq t$, where t is the maximum EC level that does not restrict yield due to salinity, and the percentage of yield reduction at higher EC levels than t is equal to s per unit increase of the EC above t .

Savvas, 2001

> 6.5–7.0 is attributed to the increasing transformation of H_2PO_4^- into HPO_4^{2-} , which is not readily taken up by plants. Furthermore, the precipitation of calcium phosphate at pH values > 6.2 is an additional reason to maintain the pH below this level in the root zone of soilless-grown plants. The occurrence of Fe-, Mn-, Zn- and Cu-deficiencies at pH values > 6.5–7.0 is associated with increased conversion of these nutrients into insoluble forms which precipitate. In the case of manganese, the precipitation of water-insoluble Mn forms at relatively high pH is further accelerated by an increased activity of Mn-oxidizing bacteria. Iron is the micronutrient with the lowest solubility at high pH. In solution cultures, the free iron ions precipitate even at pH values below 6.5, mainly as iron phosphate. Therefore, Fe should always be added in the form of Fe-chelates in hydroponics, preferably as Fe-DTPA or Fe-EDDHA.

When the pH of the nutrient solution in the root zone drops to levels below 4.5–5.0, both plant growth and yield may be impaired. The detrimental effects of low pH levels on growth and yield are mainly attributed to Mn and Al toxicities due to solubilization of various oxides and hydroxides of Mn and Al, which are constituents of the substrate and remain insoluble at pH levels over 5. In addition, the uptake of Ca, Mg and K by the plants may also be restricted at $\text{pH} \leq 4$ in the root zone, especially if the low pH was imposed by a relatively high $\text{NH}_4\text{-N}$ concentration in the nutrient solution. At pH levels below 4 in the root zone, direct H^+ injury to the roots may be observed.

Theoretically, nutrient availability is optimal when the nutrient concentrations in the root zone correspond approximately to the nutrient-to-water uptake ratio. Under such conditions, plants do not have to consume energy to take up or to actively exclude any nutrient ions, whose concentrations are lower or higher than their nutrient-to-water uptake ratios, respectively. However, the nutrient-to-water uptake ratios fluctuate widely in response to different climatic conditions, even within the same day. Therefore, it is not possible to provide a nutrient solution with nutrient concentrations which would be continuously in accordance with the corresponding nutrient-to-water uptake ratios. On the other hand, due to the very low volume of nutrient solution per plant, changes in the nutrient-to-water uptake ratio might quickly result in large alterations of the ionic concentrations in the solution. Indeed, due to a more intensive plant uptake during particular time intervals, some nutrients may become depleted while others may accumulate. Therefore, most investigators suggest higher nutrient concentrations than the expected mean nutrient-to-water uptake ratios, in order to ensure adequate supply of all nutrients. Recommended nutrient concentrations for nutrient solutions prescribed to specific plant species grown in greenhouses are given in Table 2.

Different plant species have different preferences with regard to nutrient ratios in the nutrient solution. Thus, the determination of the most favourable nutrient ratio for each species is of major importance. Most experiments concerned with

effects of nutrient ratios in nutrient solutions focused on the ratio between the metallic macronutrients (K:Ca:Mg or K:Ca), nutrient anion ratios, the N:K (or K:N) ratio and the ratio of NH_4^+ to total nitrogen. The ratio between the metallic macronutrients is important for the maintenance of the EC in the root zone, since excessively high Ca:K or Mg:K may result in accumulation of these ions. Furthermore, the K:Ca:Mg ratio has a strong impact on the occurrence of physiological disorders, especially in fruit vegetables (Savvas *et al.*, 2008). The N:K and N:S proportions in the nutrient solution are important for the maintenance of a balance between vegetative and reproductive growth and fruit quality (Savvas, 2001). The proportion of $\text{NH}_4^+\text{-N}$ to total nitrogen has no impact on the total supply of N to the crop via the nutrient solution, since both NH_4^+ and NO_3^- are N sources. However, ammonium to total nitrogen ratio is very important for the regulation of pH in the root environment.

Impact of nutrition on produce quality

Some consumers are rather mistrustful with regard to vegetables produced in soilless cultivations. This attitude is mainly based on the assumption that the soilless cultivation of plants is based on the extensive use “chemicals”, unlike plants grown in soil which acquire “natural substances” for their nutrition. However, this belief is not based on scientific knowledge. It is well known that higher plants need only inorganic substances, mainly in ionic form, to satisfy their nutritional requirements.

Plants take up N as NO_3^- and NH_4^+ but not in the form of organic N substances, regardless of the content of organic matter in the soil. Actually, the organic N compounds have to be converted into inorganic N forms before they can be taken up by plants. Consequently, with respect to the quality of the edible vegetable products, it is completely irrelevant whether the nitrogen contained in the plant tissues stems from the organic substances of the soil or from inorganic fertilizers. The only factor influencing the vegetable quality is the quantity of absorbed nitrogen and the way in which it is utilized in the plant metabolism, which has an impact on the $\text{NO}_3\text{-N}$ concentration in the edible plant tissues. However, both these factors are better managed in soilless culture, since the small volumes of rooting medium applied in soilless culture enable a more efficient control of the nutrient supply through the composition of the nutrient solution. Thus, reducing the nitrate nitrogen concentration in the nutrient solution supplied to lettuce or other leafy vegetables for some days prior to harvesting may considerably lower the NO_3^- content in the leaves of the plants, without significant yield losses. Moreover, since in hydroponics the plants are grown in substrates, which are free from pathogens when they are initially supplied to the grower, the pressure from soil-borne diseases is much weaker than in soil-grown crops. As a result, the demand for use of soil-disinfecting chemicals is considerably reduced in soilless culture, with obvious advantages for the quality of the vegetables produced. Finally, the taste of some fruit vegetables, such as tomato and melon, may be

substantially improved in hydroponics by manipulating the total salt and nutrient concentration in the supplied nutrient solution. Nevertheless, many other factors influencing plant growth are different in soilless cultivated crops than in soil-grown crops. Most of these factors also affect the quality of harvested vegetables.

Monitoring and adjusting the nutrient supply

As a rule, the target nutrient concentrations in the nutrient solution supplied to soilless cultivated crops are different from the optimal concentrations in the root environment. This is the result of dissimilarities in the efficiency of plants to take up different ions owing to the involvement of different absorption mechanisms in each case. Therefore, when instructions regarding the nutrition of a particular plant species in soilless culture are given, it is essential to recommend at least two target nutrient solution compositions, particularly one for the solution supplied to the crop and another one for the solution in the root environment. The nutrient concentrations in the root environment are of paramount importance, since the plant senses and responds to the nutrient status prevailing around its roots. The composition of the nutrient solution supplied to the crop is also very important, although it has only an indirect impact on crop performance, since it is the main tool to achieve and maintain the nutrient concentrations close to the target levels in the root zone. The plant requirements for any particular nutrient may change, independently of those for other nutrients, in the different plant developmental stages. Hence, for plants with a long harvesting period (e.g. tomato) it is better to suggest different target nutrient solution compositions for different plant developmental stages.

If the nutrient concentrations in the supplied solution are balanced, monitoring the solution's EC in the root environment is a good tool to check plant nutrient status. Nevertheless, a chemical analysis in a representative sample of substrate or nutrient solution taken from the root environment at regular intervals (e.g. every month), especially in closed hydroponic systems, could contribute to better and safer nutritional management of the crop. However, the control of the EC in the root environment provides no information on the micronutrient concentrations. Therefore, care should be taken to apply proper target micronutrient concentrations in the supplied nutrient solution. As a rule, the pH maintained in the root zone is more important for micronutrient availability than the macronutrient concentrations *per se* in the supplied solution. Hence, monitoring the nutrient solution pH in the root zone provides an indirect index regarding the availability of micronutrients for the crop. However, especially for some microelements, the concentration in the supplied nutrient solution is crucial. This is the case with boron, which has a narrow range of optimal concentrations in the nutrient solutions supplied to soilless crops.

A frequent problem in soilless culture is the increase of the EC in the root zone, reaching higher levels than the salinity threshold value for the corresponding plant

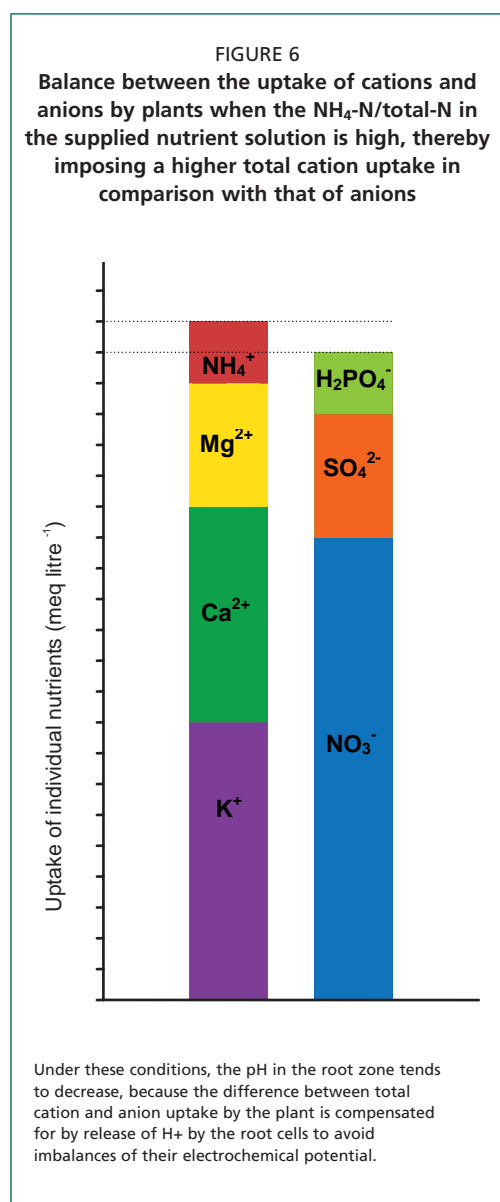
species. The most efficient strategy to prevent an increase of the EC in the root zone of soilless cultivated plants to harmful levels is the use of good quality water. However, in the Mediterranean region, irrigation water of good quality may be not available. Therefore, other measures have to be deployed to adjust the EC in the root zone. In many cases, a too high EC may be corrected by increasing the irrigation frequency. Other measures to control the EC in the root zone include:

- appropriate K:Ca:Mg ratios in the nutrient solution supplied to the crop aimed at minimizing Ca and Mg accumulation;
- correct irrigation scheduling with respect to the frequency of the water supply and the target leaching fraction; and
- appropriate adjustment of the target EC in the nutrient solution supplied to the crop by taking the EC and the composition of the drainage solution into consideration.

To optimize irrigation scheduling, the frequency of irrigation should be related to the energy input (solar radiation, heating) and suitable equipment should be used. The use of raw irrigation water to wash out salts from substrates is an erroneous practice, resulting in excessively high pH levels and nutrient imbalances in the root zone, unless rainwater is available.

The composition of the nutrient solution in the root zone changes gradually, due mainly to selective ion uptake by the plants in accordance with their nutrient requirements. In periods of sufficient light intensity and rapid growth, the anion uptake usually exceeds that of cations, owing to elevated nitrate absorption and utilization in plant metabolism. In terms of electrochemical potential, anion uptake which exceeds that of cations is compensated for by the release of HCO_3^- and OH^- by the roots. As a result, the pH of the nutrient solution in the rhizosphere increases. However, under poor light conditions, the nitrate reductase activity declines, thus imposing a depression in nitrate utilization by the plant and concomitantly lower NO_3^- uptake rates. Consequently, the total anion uptake is reduced. In terms of electrochemical potential, a more rapid uptake of cations than anions is compensated for by release of H^+ from the roots. Hence, under poor light conditions, the root zone pH does not tend to increase rapidly, and in some cases it may even decrease.

If the pH of the nutrient solution in the root zone drops below the optimal range, KOH, KHCO_3 or K_2CO_3 may be used for its adjustment, injected from a separate stock solution tank to avoid phosphate and carbonate precipitation (Savvas, 2001). The control of pH in the root environment of soilless cultivated plants usually requires measures to prevent the occurrence of a too high, rather than a too low, pH. If the percentage of drainage solution is relatively low, increased irrigation frequency or water dosage at each irrigation cycle might restore normal pH levels within the root zone. If adjustment of the irrigation schedule fails to



bring the pH to normal levels, an increase in ammonium supply may be needed. Nitrogen is the only nutrient that can be supplied to plants via fertigation in both anionic (NO_3^-) and cationic (NH_4^+) forms, while the uptake rates of both N forms are influenced by their external concentrations. Thus, the manipulation of $\text{NH}_4\text{-N}/\text{NO}_3\text{-N}$ in the supplied nutrient solution without altering the total-N concentration may considerably modify the total cation to anion uptake ratio. However, changes in this ratio have a profound impact on the pH of the root zone. Indeed, the imbalance of total cation over anion uptake in the rhizosphere originating from enhanced NH_4^+ uptake (Figure 6) is electrochemically compensated for by the release of protons, which results in a lowering of the medium pH. Similarly, the excess of anion over cation uptake due to increased supply of NO_3^- is compensated for by H^+ influx or equivalent anion extrusion, which increases the pH of the external solution.

As a rule, the use of NH_4^+ as the sole or dominating N source impairs growth and restricts yield due to the high toxicity of ammonia at intracellular level. Therefore, the current recommendation for soilless culture is that $\text{NH}_4\text{-N}$ should not exceed 25 percent of the total nitrogen supply (Sonneveld, 2002), although individual species differ in their response to the $\text{NH}_4\text{-N}/\text{total-N}$ supply ratio and root zone pH.

In soilless-grown crops of leafy vegetables, such as lettuce and rocket, a partial substitution of NH_4^+ for NO_3^- in the nutrient solution may restrict the accumulation of NO_3^- in the edible leaves. On the other hand, an elevation of the $\text{NH}_4\text{-N}$ supply in fruit solanaceae crops grown in soilless culture systems may increase the incidence of blossom end rot and other Ca-related disorders in fruits.

Nutrient recycling in closed soilless culture systems

In closed systems, the nutrient concentrations in the solution supplied to the crop are largely determined by the composition of the recycled drainage solution. However, it changes during the cropping period and hence its composition is unknown. The changes in the nutrient concentration of the drainage solution complicate its recycling, because the amounts of nutrients needed to establish the target concentrations in the solution supplied to the plants are uncertain. The problem is further complicated by the fact that in commercial horticulture the replenishment process must be performed automatically. To overcome this problem, various automation techniques involving measurements of drainage solution characteristics and adjustments in real time are used in modern closed-cycle soilless culture systems. A standard technique involves mixing of drainage and water at an automatically adjustable ratio by aiming at a preset EC in the outgoing mixture. This operation enables the maintenance of a constant, desired EC in the nutrient solution supplied to the crop by dispensing nutrients at standard injection rates to the mixture of drainage solution and water, despite any fluctuations in the composition of the drainage solution. Another approach is the injection of fertilizers into water at standard rates aimed at a preset EC and the subsequent mixing of the obtained solution with the effluents to be recycled. Also in the latter case, the mixing process is automatically adjusted in real time to a ratio resulting in a constant target EC in the outgoing irrigation solution.

As stated above, both techniques are based on the injection of nutrients at standard rates, which are adjustable by the grower when the drainage solution is mixed with fertilizers and water prior to its resupply to the crop. If, for a particular crop species, experimentally established estimates of the mean uptake concentrations are known for all nutrients to be added in the nutrient solution, the rates of nutrient injection may be adjusted to equal levels with the anticipated uptake concentrations. Thus, as long as the system is closed, the rate of nutrient and water input into the closed system is equal to the rate of their removal due to plant uptake. Consequently, the supply of nutrients is adequate for optimal plant growth, but not excessive, and thus neither depletion nor accumulation of nutrients occurs in the closed system. Unfortunately, nutrient solution compositions corresponding to anticipated mean uptake concentrations, which can be used for balanced crop nutrition in closed soilless culture systems, are currently available only for the climatic conditions of the Netherlands (De Krij *et al.*, 1999). Hence, to optimize nutrient recycling in soilless culture in the Mediterranean region, there is a need to establish and validate estimates of the mean uptake concentrations for all nutrients under the specific climatic conditions.

Long-term recycling of leachate solution may result in accumulation of sparingly absorbed ions, such as Na^+ and Cl^- . In order to ensure an adequate nutrient supply in closed soilless cultivations when the Na^+ and Cl^- levels in the irrigation water are not low, it is important to monitor salt concentrations in the

drainage solution so as to assess their contribution to the total EC in the outgoing nutrient solution, which can then be adjusted in real time to a value that would ensure a constant nutrient supply to the crop. However, reliable tools providing real-time monitoring of specific ion levels in the drainage solution are currently not available at prices affordable to the growers. Therefore, the standard practice for coping with salt accumulation in closed systems is currently the provisional suspension of recycling and the discharge of the drainage solution until its EC returns to acceptable levels.

IRRIGATION MANAGEMENT IN SOILLESS CULTURE

Irrigation management includes water transport to the root zone and the decisions “when” to irrigate the crops and “how much” to apply. Irrigation scheduling requires good knowledge of the crop’s water demand and the substrate’s physical properties. The efficiency of the irrigation method affects the precision of water application. Irrigation management is one of the main factors determining the overall performance of soilless culture systems, since both nutrients and water are supplied to the root zone via the irrigation system. One of the most important advantages of soilless culture compared with soil-grown cultures is the accurate control of water availability in the root zone. Moreover, soilless culture systems greatly improve water-use efficiency and water management in crop production. However these advantages depend on the equipment available and the system management because of the low buffering capacity in soilless culture systems.

In soilless culture, the root zone volume is much smaller than in soil-based cropping systems and thus the total volume of available water per plant is smaller, despite the higher water-holding capacity, lower moisture tension and greater hydraulic conductivity in most crops grown on substrates (Schröder and Lieth, 2002). Smaller root volume results in restricted root length and surface area and, therefore, limited capacity of the plant to take up nutrients and water. Therefore “little and frequent” irrigation and fertilization is applied to maximize yield. A standard recommendation in soilless culture is to apply a constant volume of irrigation water at each irrigation event and vary the number of irrigation applications (as opposed to keeping the number of irrigation events constant and varying the volume of irrigation water).

Some growing media may be characterized by a high water-holding capacity accompanied by suboptimal air capacity, while other media may exhibit high air capacity accompanied by suboptimal water availability. In the first case, less frequent irrigation in combination with higher watering dosages is the most appropriate strategy, while the opposite is recommended in the second case. As a general rule, the application of a specialized irrigation schedule for each growing medium, taking into consideration the physical properties, may mitigate problems relating to poor aeration or limited water availability.

Characteristics of irrigation systems

Various types of irrigation system are used, depending mainly on the soilless culture system applied in each case. In most cases, there is more than one irrigation circuit or sector in one greenhouse aimed at reducing the necessary output capacity of the irrigation pump. System design should aim to maximize irrigation performance by optimizing all design characteristics, including system capacity, uniformity, storage capacity, pumping capacity, delivery systems, management of drainage, production unit and automation control systems.

Capacity

System capacity is the maximum flow rate that can be delivered through a particular irrigation system. It is related to the volume of water applied through each circuit and the duration of each irrigation event.

Uniformity

Uniformity is important when the irrigation water is supplied through a large number of emitters, especially when each plant receives nutrient solution through an individual emitter. Even if the capacity of the system is sufficient to cover the total water and nutrient requirements of a crop, some plants may receive insufficient amounts of nutrient solution while other plants may be overirrigated if the variation in flow rate among the emitters is very high. The variation in flow rate among individual emitters determines the uniformity of the system. Uniformity is key to the designing of irrigation systems. The uniformity of an irrigation system can be quantitatively estimated by calculating the coefficient of uniformity (Q) using Equation 2:

$$Q = 1 - \frac{\sum_{i=1}^n |x_i - A|}{nA} \quad \text{Eq. 2}$$

where:

x_i is the water supply rate in the i^{th} of the n sample plants

A is the mean water supply rate to the particular plants

The coefficient of uniformity is a dimensionless quantity, independent of the water supply rate with a range of 0–1. The higher the coefficient of uniformity, the more uniform the distribution of water to the plants. Irrigation uniformity can be increased by minimizing the pressure drop in the system and pressure variation among the emitters. In order to distribute the nutrient solution uniformly in soilless-grown crops, well-designed and well-maintained irrigation systems should be established. The uniformity of an irrigation system decreases over time, due to partial or complete clogging of emitters.

Storage capacity

A storage tank or reservoir is required to supply irrigation water to the plants. The necessary volume of the storage tank depends on the size of the growing system,

namely number and type of plants and their water demand when they reach maximum size under maximum evapotranspiration conditions. A storage tank is anticipated to have sufficient capacity to supply irrigation water for at least one day to all plants. A high storage capacity minimizes the risk of crop damage due to failures in the primary water supply system.

Pumping capacity

The pumping capacity needed depends on the size and type of the irrigation system, number of irrigation zones, crop species, water requirement and extent of each circuit. It is important for the grower to know the maximum potential demand for irrigation water and the pumping capacity required to satisfy this, even in a worst-case scenario (Schröder and Lieth, 2002). Soilless culture systems have small root zone buffering and, therefore, the plants need more frequent irrigation, which entails short intervals between irrigation events. Overall, irrigation timing and duration is related to environmental conditions, cultivated plant species and growth stage.

Delivery systems

Irrigation systems can be grouped according to the method of water delivering to the plant, namely overhead (above the plant), drip irrigation (at the substrate surface) or subirrigation (below the root zone). Solenoid valves are used to automatically control irrigation.

If no substrate is used or the substrate has limited water-holding capacity, continuous supply of nutrient solution in closed-loop circuits enabling capture and reuse of the effluents is appropriate. In such systems, there is no need to define when to irrigate and how much water will be applied, since the roots are either

constantly immersed in a continuously flowing nutrient solution (i.e. NFT) or frequently sprayed with nutrient solution (e.g. aeroponics).

Overhead systems

Water or nutrient solution is applied directly to the shoot from above. The use of overhead irrigation systems (e.g. the so-called “boom system”) is very common in nurseries for seedling and pot plant production (Plate 15). A boom system consists of a rig that moves above the plants by means of a rail. An irrigation pipe equipped with nozzles at standard intervals is fixed on the rig. The uniformity of a boom system depends on the design



Plate 15

Boom system in vegetable seedling production

and layout of the nozzles on the boom, the consistency of water pressure in the supply and the uniformity of speed at which the boom runs over the plants (Schröder and Lieth, 2002).

Drip irrigation

Drip irrigation is the most widely used system in soilless culture due to its high precision and uniformity, resulting in highly efficient water use. Water is delivered slowly to the roots either on the substrate surface or directly to the root zone.

A drip irrigation system consists of one or more pumps, non-return valves, dilution equipment, filters, pressure regulators, water meters, mainline, submainlines, lateral pipes and emitters. The pump should be selected according to maximum expected flow rate and pressure. Filters are used to prevent clogging, and pressure regulators are important to provide uniform pressure in the system. Various emitters are available in a wide range of shapes and flow rates. Pressure-compensating emitters which deliver a constant amount of water per unit of time regardless of changes in pressure are a recently developed technology. Emitters should be selected on the basis of their advantages and disadvantages and their specific suitability for each type of soilless cultivation system (Table 3). The flow rate suggested for each emitter ranges between 1 and 4 litres per hour, depending on the cultivated plant species, soilless culture type and irrigation system capacity. Various emitters are available to provide this range of flow rate and most are designed to operate at a supply pressure of 0.2–1 bar. Substrate particle size also affects water availability and needs to be taken into consideration in the selection of emitters. For example, in a substrate with large particles, the use of low density emitters with high flow capacity results in a more vertical movement, while high density emitters with a low flow capacity causes more horizontal flow, which is desirable (Schröder and Lieth, 2002).

Overhead systems

Advantages:

- Relatively low installation cost
- Applicability in large areas
- Cooling effect

Disadvantages:

- Waste of water due to unused runoff
- Disease incidence risk
- Residue risk on leaves and flowers
- Inefficient water use in substrate culture resulting in lower WUE
- Wetting the surrounding area of the plant

Drip irrigation

Advantages:

- Individual irrigation of each plant
- Efficient water use
- Precision
- Uniformity
- Less runoff
- Less evaporation

Disadvantages:

- Emitter clogging
- Difficulty in evaluating system operation and application uniformity
- Substrate/application rate interaction
- Persistent maintenance requirements
- Smaller wetting pattern

TABLE 3

Categories of emitters, advantages and disadvantages, and their suitability for different soilless growing systems

Emitter	Advantages	Disadvantages	Growing system
Porous pipe	Easy, low cost	Irregularity among the pores, no internal water pressure control	Surface or subirrigation systems
Punch-in emitters - drip emitters - in-line - misters	Precise, well moist root zone	Not flexible for plant spacing	Containers, pot plants Misting and air humidifying
Emitter lines	Pressure-compensating emitters can be easily installed, lower cost, long life	Life depends on quality	Trough culture
Spray emitters	Operation at low pressure	Lower water-use efficiency, water loss due to evaporation	Substrate benches, thin layer systems with high plant density

The spaghetti or tube system has a small diameter tube connected at the side. The system can be used with or without emitters. Since each plant has its own tube, it is more suitable for pot plants and containers. Pressure fluctuation could be prevented by using pressure-compensating emitters.

Subirrigation

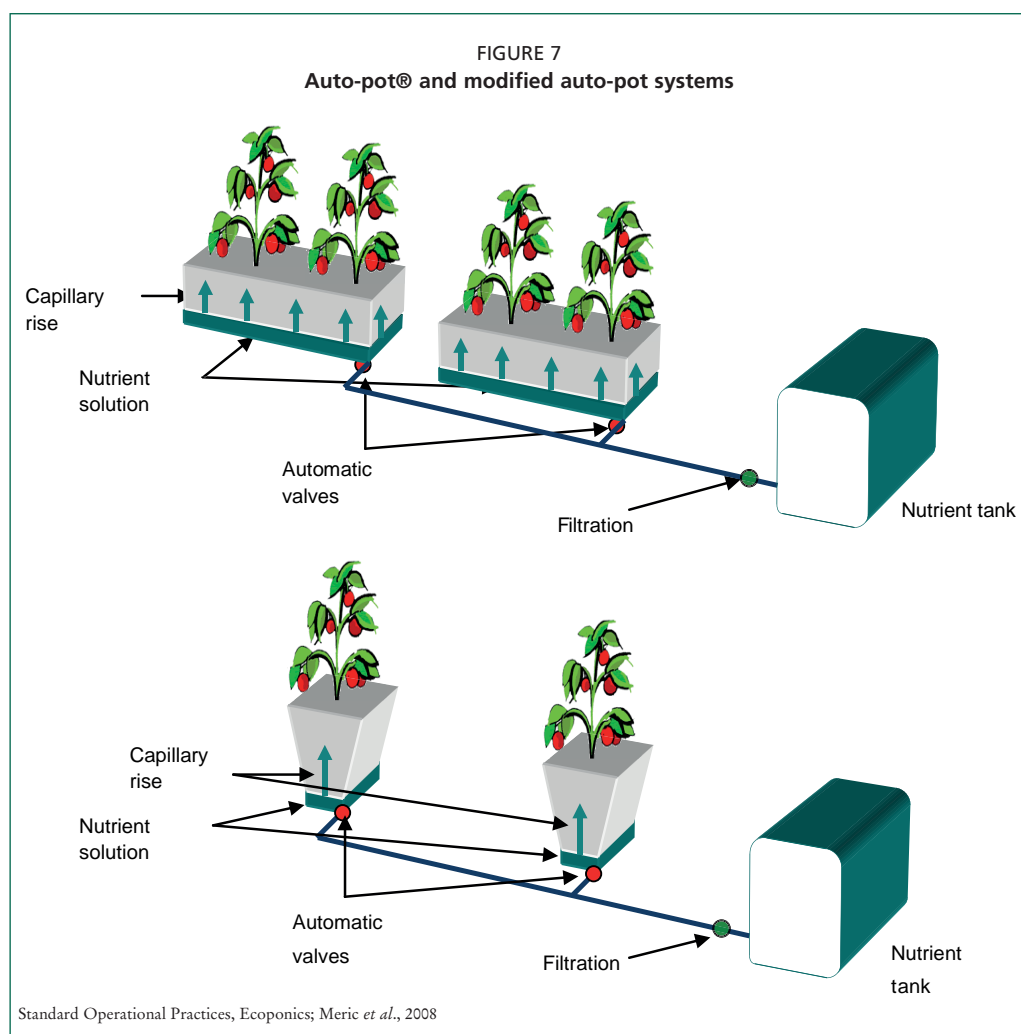
In subirrigated soilless cultivations, nutrient solution is applied from the base and moves up through the root zone by capillary forces – it could be called “plant-driven irrigation”. These systems consist of capillary mats, trough benches, ebb and flow systems, flooded floors (Lieth and Oki, 2008) and auto-pots® (Fah, 2000) (Table 4) (Figure 7).

In a standard subirrigation system, the nutrient solution is pumped from the fertigation head to the upper end of the crop benches, released into the troughs

TABLE 4

Categories of subirrigated systems, advantages and disadvantages, and their suitability for different soilless culture systems

System	Advantages	Disadvantages	Crop grown
Capillary mats	Easy, cost effective	Needs good ground levelling	Pot plants
Troughs	Different amount for different plant groups	If system not closed, waste of water	Pot plants, vegetables grown on substrates
Ebb and flow system	Easy to use; uniformity	Substrate and water depth interaction; if recycling applied, spread of pathogens	Young plants, vegetables
Flooded floors	Larger scale	Needs proper design and installation; sanitation	Seedling production, big ornamental plants
Auto-pots®	No leaching of nutrients and water; no electricity-driven devices; low cost	Salt accumulation in the upper part; needs smart valves for capillary action	Vegetables, short cycle crops



and allowed to run slowly down to the lower end of the trough where the excess drains out and returns to a catchment tank for recirculation. In most cases, the supply of nutrient solution is intermittent. The troughs are filled with a substrate with good capillary properties. For better drainage after each irrigation cycle, a coarse aggregate may be placed in the bottom of the trough.

In auto-pot® systems, water and nutrients are supplied when a smart-valve is opened and the nutrient solution enters the bottom of the container to a predetermined and preset depth (usually 3.5 cm). The valve then closes, preventing further entry of nutrient solution until the original supply has been conveyed from the solution chamber to the pot and then to the plant. The solution reaches up to the higher layers of the pot and down to the root surface (essential for plant uptake) by capillary action thanks to the porosity of the substrate. Once the

solution is absorbed, the valve is reopened to supply water and nutrients to the containers (Fah, 2000).

Most subirrigation systems do not discharge nutrient solution to the environment; they are superior to other systems in terms of water and fertilizer saving, uniformity of nutrition, labour efficiency and self-scheduling. Subirrigation is mainly applied in pot plant production, given the short growing cycle and low water and nutrient requirements. Its main disadvantage is root zone salinity resulting from application of the nutrient solution from the bottom and its upward movement in the bulk of the substrate, which does not permit salt leaching. One way of reducing salt buildup and its negative effects on plants in subirrigated systems is to supply nutrient solutions with lower macronutrient concentrations (Tuzel *et al.*, 2007).

Management of drainage

Drained nutrient solution is discarded outside the greenhouses in open systems while it is collected and reused in closed systems. In open soilless culture systems, the drained solution can be used in open field crops instead of being released into the environment. In closed systems, the drainage solution is captured and recycled. However, the accumulation of some nutrients due to dissimilarities between the rates of nutrient supply and the rates of nutrient uptake results in ion imbalance. On the other hand, the risk of root disease spreading through the recycled nutrient solution is another important problem that should be considered. Use of sand filters or UV lamps can minimize the risk of pathogen dispersal through the recycled drainage solution but the additional cost has to be taken into account.

Control systems

There are different levels of irrigation control, from hand irrigation and simple clock timers to computer-based monitoring and control systems. With manual control, substrate selection (i.e. substrate with high water-holding capacity, good aeration and high hydraulic conductivity) is important to mitigate the impact grower error. Control parameters depend on crop species, growing stage, environmental conditions, system performance and management practices. Controls must be extremely dependable, and should have a signalling system if failure occurs. Also a backup control system or an override to manual operation is important for triggering irrigation events.

Irrigation scheduling

Irrigation scheduling approaches

Irrigation scheduling is the decision related to “when” to irrigate and “how much” water to apply to the crop. It is based either on substrate water status, where the moisture content or potential is measured directly to determine the need for irrigation, or on plant water status, which does not indicate how much water to apply. The main advantages and disadvantages of the different irrigation

scheduling approaches are summarized in Table 5 (Jones, 2004). However, not all these approaches are as yet used in soilless culture.

In soilless culture, little and frequent irrigation is required. Thus, rapidly growing crops in the summer may need 15–20 or even more irrigation events a day. Increasing irrigation frequency reduces fruit defects, such as cracking and blossom end rot. To optimize synchronization of water supply to demand in soilless cultivated crops, frequency and rate of irrigation must be properly tuned. The quantity of supplied water is higher than anticipated plant consumption to

TABLE 5
Main advantages and disadvantages of some irrigation scheduling approaches according to Jones (2004)

Approach	Advantages	Disadvantages
I. Substrate water status (root zone sensors)	Directly measures matric potential and water content in root zone.	Indicates plant status indirectly.
a) Substrate water potential (i.e. tensiometers)	Simple, easy to apply, quite precise, appropriate for automation.	Needs many sensors and good contact with the substrate; position should be representative for root zone.
b) Substrate water content (time domain reflectometer – TDR; frequency domain reflectometer – FDR)	Simple, easy to apply, quite precise, appropriate for automation, measures root zone EC.	FDR and TDR need calibration; position should be representative for the root zone; needs good contact with substrate; expensive.
II. Plant water status	Measures plant response to stress directly, integrates environmental conditions, potentially very sensitive.	Does not indicate “how much” water to apply; calibration required to determine “control thresholds”; still little use in commercial greenhouses.
a) Tissue water status	Appropriate measurement for physiological processes (i.e. photosynthesis); particularly measures leaf water status.	Sensitive to environmental conditions.
i) Psychrometer (ψ)	Valuable, thermodynamically based measure of water status; can be automated.	Requires sophisticated equipment and high level of technical skill, unreliable in the long term.
b) Physiological responses	Potentially more sensitive than measuring tissue (especially leaf) water status.	Require sophisticated or complex equipment; require calibration to determine “control thresholds”.
i) Stomatal conductance – Porometer	Very sensitive response. Accurate: the benchmark for research studies.	Needs replications for reliable data. Needs labour (not automated); inappropriate for commercial crops.
ii) Growth rate	Very sensitive to stress.	Instrumentation delicate and generally expensive.
III. Model-based estimation of water needs using real-time measurements of climatic parameters	Simple, sensitive, suitable for automation.	Needs efficient calibration to specific crop species, crop growth stage and environmental conditions. Accuracy may be insufficient when cultivars or cultural practices are not those used for calibration. Some coefficients are based on poorly applicable simplifications in commercial greenhouses.

compensate for lack of uniformity in supply rate among emitters and to prevent salt accumulation in the root zone. The volume ratio of drained solution to water applied is called leaching fraction. In open soilless culture systems, the leaching fraction should not exceed 25–35 percent to minimize discharge of fertilizer residues to the environment, but in closed systems, drainage water is reused and irrigation frequency can be much higher than in open cultivation systems.

Frequent irrigation resulting in high leaching fractions in closed soilless culture systems can delay salt accumulation rate in the root zone, enhance yield and improve fruit quality without any environmental impact. The only precaution regarding the application of a frequent irrigation schedule is the possible creation of excessive moisture conditions in the root zone that might reduce oxygen availability (Schröder and Lieth, 2002). Nevertheless, this problem may be tackled by selecting growing media with optimal physical characteristics in combination with proper placement of the media in the hydroponic installation.

Irrigation decisions

Generally, common approaches in irrigation decisions entail timer-based, sensor-based or model-based irrigation control methods.

- Electrical timers specifically designed to control irrigation valves are used. This operation is the cheapest, simplest and easiest approach for triggering irrigation events. However, time-based irrigation needs skilled personnel and knowledge to compile a present irrigation schedule.
- Sensor-based control depends on the measurement of the water status either in the substrate (i.e. tensiometer, frequency domain reflectometer) or in the plant (i.e. sap flow meter, thermal sensing) (Table 5).
- Model-based control is based on the estimation of plant water loss related to one or more environmental variables (i.e. temperature, solar radiation). Scheduling is computerized to obtain in real time crop irrigation needs based on the data provided online by sensors. Many methods are available for the estimation of evapotranspiration and most of them use either a modified version or a combination of models originally developed by Penman and Monteith. However, the application of these models in commercial practice needs appropriate calibration for each crop.

Impact of irrigation on yield and quality

Freshness and appearance, including fruit or organ size, colour and the occurrence of physiological disorders (e.g. cracking and blossom end rot, BER, in tomatoes and peppers, and tip burn in lettuce) are directly or indirectly influenced by water availability and quality, and watering frequency. Controlled watering could be used to balance vegetative growth with generative development in fruiting vegetables and to regulate fruit size (e.g. in tomatoes). Generally, increasing water availability enhances fruit size and acidity in tomato. On the contrary,

deficit irrigation enhances fruit desirability in terms of dry matter content, total soluble solids, sugar and colour intensity. Fruit sugars become concentrated under conditions of reduced water supply. However, the problem of BER is difficult to solve since the conditions contributing to increased dry matter and sugar concentrations also favour this disorder. Calcium spraying on the fruit cluster or improving environmental conditions (Gruda, 2005) are possible solutions.

Water shortage can increase the content of health-promoting substances. Water availability and irrigation timing may also influence the flavour of vegetables. Overall, water shortage generally tends to increase the ascorbic acid content in fruit; increasing the water supply reduces lycopene, β -carotene, vitamins and minerals, as well as total antioxidant capacity. High yields do not automatically imply high quality, therefore, a compromise needs to be established (Gruda, 2009).

SOILLESS CULTIVATION OF MAJOR GREENHOUSE VEGETABLE CROPS

The soilless cultivation specifics of the major vegetables cultivated commercially in Mediterranean greenhouses are given below, including most used systems, layout, crop nutritional requirements and other special needs. The crops are divided into two groups: fruiting vegetables and once over-harvested vegetables. For each vegetable species, recommended nutrient concentrations in nutrient solutions are given (Savvas, 2012), based on Dutch recommendations (Sonneveld and Straver, 1994; De Kreij *et al.*, 1999) modified on the basis of mostly unpublished experimental data to adapt to Mediterranean climatic conditions. In addition to the nutrient concentrations recommended for open soilless crops of tomato grown on inert substrates, nutrient solutions for closed soilless cultivations are given, as well as target nutrient concentrations for the root zone. The recommended EC values are valid for NaCl concentrations up to $1.5 \text{ mmol litre}^{-1}$ in the irrigation water. If Na^+ and Cl^- exceed this level in the irrigation water, the target EC has to be increased accordingly, taking into account that $1 \text{ mmol litre}^{-1}$ of NaCl raises the EC by 0.115 dS m^{-1} (Sonneveld, 2002).

Fruiting vegetables

This category includes tomato, cucumber, bell pepper, eggplant, melon and bean. The general characteristic of this group is the long cropping period, 1–3 plantings per year and a small number of plants per m^2 (about 1–6), arranged in 2–4 rows per 3.2- or 4-m span (van Os *et al.*, 2008). Fruiting plants are characterized by a complex crop physiology, since the vegetative growth and flowering as well as the fruiting phases overlap and need to be simultaneously and continually balanced. Young plants are raised in blocks and planted either on substrates supplied regularly with nutrient solution or directly in pure nutrient solution when liquid hydroponic systems are employed.

Tomato

Tomato (*Solanum lycopersicum* L.) is the most important greenhouse crop grown in soilless cultivation systems. The need to obtain high yields of high quality while considering environmental issues puts increased pressure on greenhouse tomato growers. Soilless culture systems are sustainable while increasing the net income per invested square metre; in addition, today's varieties allow growers to use a wide range of new fresh tomato types. The aim is to produce greenhouse tomatoes in periods when outdoor production is not available or competitive, thereby achieving premium-priced production with high quality and good-tasting fruit. The most widely used soilless culture system for tomato production is cultivation on rockwool slabs wrapped in polyethylene bags and supplied with nutrient solution through a drip irrigation system. Other local substrates, such as perlite, pumice and tuff, are also used, whereas the NFT-system is not very common in the Mediterranean area, although it is generally considered to be a commercially viable form of water culture with ecological benefits.

In soilless culture, tomato can tolerate total salt concentrations of up to 2.5–2.9 dS m⁻¹ in the root zone without yield losses (Sonneveld and Voogt, 2009). However, in most cases, growers maintain higher EC levels than the STV in the root zone of soilless-grown tomato in order to improve fruit quality in terms of organic acidity and soluble solid (Gruda, 2009). The increase of EC to higher values than the STV in order to improve fruit quality is economically beneficial despite the concomitant yield losses because of the relatively low rate of tomato yield decrease per unit of EC increase above the STV (Sonneveld and Voogt, 2009). Under Mediterranean conditions, EC values of up to 3.5 dS m⁻¹ in the root zone are recommended for soilless tomato in order to achieve premium fruit quality. In north European countries, even higher EC values of up to 5 dS m⁻¹ are maintained, particularly under cold and cloudy weather conditions. Nevertheless, the EC of the nutrient solution in the root zone of tomato grown in Mediterranean greenhouses has to be reduced to levels lower than 3 dS m⁻¹ under hot summer conditions. In addition to the EC adjustment in the root zone, Gruda (2009) reported several other ways to improve product quality by proper design and operation of soilless culture systems. Furthermore, a review of recent research relevant to the impact of tomato nutrition on fruit quality was written by Passam *et al.* (2007).

A crucial factor for tomato nutrition in soilless culture is the N:K ratio in the nutrient solution. Adams and Massey (1984) found that the mean daily N:K uptake ratios were 2.40 and 2.25 on a molar basis prior to setting of fruit in the first truss of tomato in February and August, respectively. However, this ratio decreased to 1.12 (molar basis) when the fruit load increased, followed by a slight increase to 1.40 after some weeks. Another important characteristic of the nutrient solution supplied to tomatoes is the NH₄-N/total-N ratio. As reported by Sonneveld (2002), both growth and yield of tomato are enhanced when a small part of N ranging from 5 percent to less than 15 percent of total N is supplied in the form of

TABLE 6

Recommended EC (dS m⁻¹), pH and nutrient concentrations (mmol per litre) in nutrient solutions (NS)^a for soilless tomato crops grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS ^b	SSCS ^c	RE ^d	SSOS	SSCS	RE
EC	2.80	2.50	2.00	3.20	2.40	1.85	3.40
pH	5.60	5.60	-	5.80–6.70	5.60	-	5.80–6.70
[K ⁺]	6.80	7.00	6.40	7.50	8.00	7.50	8.20
[Ca ²⁺]	6.40	5.10	3.10	7.80	4.50	2.30	8.00
[Mg ²⁺]	3.00	2.40	1.50	3.40	2.10	1.10	3.40
[NH ₄ ⁺]	0.80	1.50	1.60	< 0.60	1.20	1.40	< 0.40
[SO ₄ ²⁻]	4.50	3.60	1.50	5.00	4.00	1.50	6.00
[NO ₃ ⁻]	15.50	14.30	12.40	18.00	12.40	11.00	17.20
[H ₂ PO ₄ ⁻]	1.40	1.50	1.30	1.00	1.50	1.20	1.00
[Fe]	20.0	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	8.00
[Zn]	6.00	5.00	4.00	7.00	5.00	4.00	7.00
[Cu]	0.80	0.80	0.80	0.80	0.70	0.70	0.80
[B]	40.00	35.00	20.00	50.00	30.00	20.00	50.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

NH₄⁺. Tomato is tolerant to moderately high pH but susceptible to low pH levels in the root environment, due mainly to impairment of the Ca uptake (Savvas *et al.*, 2008). With respect to the macronutrient cations, the K requirements increase with fruit load, while Ca requirements decrease (De Kreij *et al.*, 1999). However, the Ca levels in the supplied nutrient solutions should be maintained at relatively high levels during the reproductive phase of the crop to minimize the incidence of BER. Recommended nutrient solution concentrations for tomato are given in Table 6.

Cucumber

Cucumber (*Cucumis sativus* L.) is a semi-tropical plant originating in India and the second most important greenhouse soilless-grown crop. In Greece, Turkey, Egypt and other Mediterranean countries, a short-fruit cucumber is widely grown and is very popular in local markets. However, the most common cucumbers grown today in soilless greenhouses are the long, seedless type. Cucumber can be grown in different seasons and many growers in Mediterranean countries prefer to plant two or three crops per year instead of a single, year-round crop (standard practice in the Netherlands). After termination of the first crop, plants with roots are only partially removed and cut out from the substrate with a knife. The young plants of the second set can then be inserted with a small amount of fresh substrate, if they are grown on granular substrates. After transplanting, adequate irrigation is essential for continuous growth.

Cultivation in rockwool is very common. However, other local growing media (e.g. perlite, pumice) are also used. Slabs or bags with a width of either 15 or 30 cm are employed. Since no differences in cucumber yield were found when slabs of different width were used, it is recommended to use either single-row slabs (15 cm) or double-row slabs (20–30 cm). In the latter case, the plants have to be supported by applying a V-training system.

Cucumber is a salt-sensitive plant species; the EC in the root-zone solution should ideally be maintained at 2.7 dS m^{-1} and in any case it should not exceed 3 dS m^{-1} in Mediterranean greenhouses, otherwise significant yield losses are inevitable (Sonneveld and Voogt, 2009). In Mediterranean greenhouses, EC values of 2.5 dS m^{-1} should be maintained during early plant growth, and adjusted to 2.7 dS m^{-1} with increasing plant size (Savvas, 2012). The recommended pH level in the root zone of cucumber is 5.3–6.4 and this can be achieved by including about 10 percent of the total N in the form of $\text{NH}_4\text{-N}$ in the solution. The literature provides recommended compositions of nutrient solutions for soilless cucumber (Papadopoulos, 1994; Sonneveld and Straver, 1994; De Kreij *et al.*, 1999; Sonneveld and Voogt, 2009), but these recommendations are based on research carried out under cold-winter climatic conditions. Recommended nutrient concentrations for cucumber in Mediterranean climatic conditions are given in Table 7.

TABLE 7

Recommended EC (dS m^{-1}), pH and nutrient concentrations (mmol litre^{-1}) in nutrient solutions (NS) ^a for soilless cucumber grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS ^b	SSCS ^c	RE ^d	SSOS	SSCS	RE
EC	2.40	2.20	1.95	2.50	2.10	1.85	2.70
pH	5.60	5.60	-	5.30–6.40	5.60	-	5.20–6.40
[K ⁺]	6.30	6.20	6.00	6.40	7.20	6.50	8.00
[Ca ²⁺]	5.00	4.15	3.50	6.00	3.40	2.90	5.50
[Mg ²⁺]	2.00	1.60	1.10	2.30	1.40	1.00	2.50
[NH ₄ ⁺]	0.80	1.40	1.60	< 0.50	1.40	1.40	< 0.50
[SO ₄ ²⁻]	1.90	1.30	1.00	2.20	1.40	1.00	2.60
[NO ₃ ⁻]	15.60	14.75	13.10	17.00	13.75	12.00	17.20
[H ₂ PO ₄ ⁻]	1.20	1.25	1.20	1.00	1.15	1.20	1.00
[Fe]	20.00	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	7.00
[Zn]	6.00	5.00	5.00	7.00	5.00	5.00	8.00
[Cu]	0.80	0.80	0.80	1.30	0.80	0.70	1.50
[B]	40.00	25.00	25.00	50.00	25.00	25.00	50.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

Since cucumber likes high levels of relative humidity, irrigation becomes critical at low relative humidity, because large quantities of water must be added to the growth medium without constantly flooding the roots and depriving them of oxygen. By using NFT systems or other water culture systems, additional means to improve oxygenation of the nutrient solution have to be considered (Papadopoulos, 1994).

Pepper

Bell or sweet pepper (*Capsicum annuum* L.) is the third most important soilless cultivated crop species. Bell pepper is cultivated in different growing systems and different substrates. Pepper plants can be trellised following either the Dutch “V” (a two-stem pruned) system or the “Spanish” (non-pruned) system. Jovicich *et al.* (2004) compared the “V” with the “Spanish” trellis system and found no differences in total marketable fruit yield. However, the non-pruned plants produced 38 percent more extra-large fruit and less fruit with BER at the end of the spring than the pruned plants. In addition, the labour requirement for the Spanish system was reduced to 25 percent that needed for the “V” trellis system. The authors recommend a plant density of 3.8 plants m⁻².

Pepper plants should be fertigated frequently with an appropriate nutrient solution. The suggested pH in the root zone during the harvesting period is 6–6.7, attainable by supplying about 5 percent of the total N in the form of NH₄-N. A higher NH₄-N supply during the reproductive phase is not recommended because ammonium may reduce the Ca uptake and increase the incidence of fruit with BER, to which pepper is highly susceptible. Pepper is considered a sensitive crop to salinity and the recommended EC range in the root zone is 2.7–3.0 dS m⁻¹, depending on the season of the year and the mineral composition of the available irrigation water. Detailed information on single nutrient elements and physiological disorders of greenhouse pepper, including soilless culture, can be found in a recent review by Savvas *et al.* (2008). Recommended nutrient solutions for open and closed soilless pepper crops in Mediterranean countries are given in Table 8.

Eggplant

Eggplant (*Solanum melongena* L.) is an important greenhouse crop in most Mediterranean countries. Eggplant can be grown successfully in most commercial soilless culture systems, including cultivation in substrates and nutrient solution.

When 1-m-long slabs or bags are used, two eggplant seedlings per slab or bag are usually planted. Denser spacing is not recommended because eggplant’s very large leaves may adversely affect light interception in the canopy and favour the occurrence of plant diseases. As a rule, each plant is trained to 2 or 3 stems, aiming at 4–6 stems m⁻².

TABLE 8

Recommended EC (dS m⁻¹), pH and nutrient concentrations (mmol litre⁻¹) in nutrient solutions (NS)^a for soilless pepper grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS ^a	SSCS ^b	RE ^c	SSOS	SSCS	RE
EC	2.30	2.20	1.80	2.50	2.10	1.70	2.70
pH	5.60	5.60	-	5.60–6.60	5.60	-	6.00–6.70
[K ⁺]	5.70	5.40	5.30	6.00	5.80	6.00	5.50
[Ca ²⁺]	5.30	4.65	3.15	6.50	4.50	2.70	7.25
[Mg ²⁺]	1.65	1.60	1.10	2.00	1.40	1.00	2.00
[NH ₄ ⁺]	0.50	1.20	1.40	<0.60	0.60	0.80	<0.40
[SO ₄ ²⁻]	2.00	1.85	1.00	2.70	1.75	1.00	3.10
[NO ₃ ⁻]	14.40	13.70	11.60	15.60	13.00	10.60	16.00
[H ₂ PO ₄ ⁻]	1.20	1.20	1.10	1.20	1.20	1.10	1.10
[Fe]	20.0	15.00	15.00	15.00	15.00	15.00	15.00
[Mn]	12.00	10.00	10.00	6.00	10.00	10.00	5.00
[Zn]	6.00	5.00	4.00	7.00	5.00	4.00	8.00
[Cu]	0.80	0.80	0.80	0.80	0.80	0.70	0.80
[B]	45.00	30.00	30.00	80.00	30.00	25.00	80.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

K requirements are lower during the vegetative developmental stage and increase during the reproductive stage, as the fruit load increases. Overall, the nutrient requirements of eggplant exhibit many similarities with those of tomato. The only important differences are eggplant's higher requirements of Mg and B and its lower requirements of K. However, the salt tolerance of eggplant is much lower than that of tomato and similar to that of pepper. Accordingly, the suggested EC in the root-zone solution of soilless eggplant grown in Mediterranean greenhouses ranges from 2.6 to 2.8 dS m⁻¹. Nevertheless, values up to 3.0 dS m⁻¹ may be inevitable if the NaCl concentration in the available irrigation water exceeds a level of about 3.0 mM.

Recommended nutrient solutions for soilless cultivations of eggplant grown under Dutch greenhouse conditions have been published by Sonneveld and Straver (1994) and De Kreij *et al.* (1999). Table 9 gives the nutrient solution compositions for eggplants grown in Mediterranean countries.

Melon

It is possible to cultivate two or three cropping cycles of melon (*Cucumis melo* L.) per year in substrates, such as rockwool, perlite, pumice and tuff, as well as in NFT. The transplants are raised in rockwool cubes or pots filled with a substrate, before eventually being moved into the system. As with cucumber, all emerging

TABLE 9

Recommended EC (dS m⁻¹), pH and nutrient concentrations (mmol litre⁻¹) in nutrient solutions (NS)^a for soilless eggplant grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS ^b	SSCS ^c	RE ^d	SSOS	SSCS	RE
EC	2.40	2.20	1.85	2.50	2.10	1.75	2.70
pH	5.60	5.60	-	5.50–6.50	5.60	-	5.60–6.60
[K ⁺]	5.70	5.60	5.60	5.60	6.30	6.20	6.40
[Ca ²⁺]	4.20	3.50	2.50	5.00	3.00	2.20	5.00
[Mg ²⁺]	3.00	2.50	1.65	3.70	2.30	1.25	3.80
[NH ₄ ⁺]	1.00	1.50	1.80	<0.80	1.30	1.60	<0.80
[SO ₄ ²⁻]	2.00	1.60	1.00	2.20	1.50	0.90	2.60
[NO ₃ ⁻]	15.50	14.20	12.20	16.80	13.50	11.40	17.00
[H ₂ PO ₄ ⁻]	1.10	1.20	1.00	1.00	1.20	1.00	1.00
[Fe]	20.00	15.00	15.00	25.00	15.00	15.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	7.00
[Zn]	6.00	5.00	5.00	6.00	5.00	5.00	7.00
[Cu]	0.80	0.80	0.80	0.70	0.80	0.70	0.80
[B]	50.00	40.00	30.00	80.00	35.00	25.00	80.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

flowers and laterals should be removed up to the eighth node on the main stem. One fruit is then allowed to form on each lateral. In order to improve fruit setting, melons are often pollinated by bumblebees. Rodriguez *et al.* (2006) successfully grew melons in containers filled with different substrates and supplied with a nutrient solution composed as follows (mg per litre): 50 N, 23 P, 44 K, 5 Mg, 0.2 B, 0.5 Cu, 0.1 Fe, 0.5 Mn, 0.005 Mo and 0.005 Zn. Based on practical experience and some preliminary research results, Savvas (2012) suggests a nutrient solution with an EC of 2.2 dS m⁻¹ and the following nutrient concentrations for melon grown in Mediterranean greenhouses: 6.8 mM K⁺, 4.0 mM Ca²⁺, 1.6 mM Mg²⁺, 1.1 mM NH₄⁺, 13.2 mM NO₃⁻, 1.2 mM H₂PO₄⁻, 2.1 mM SO₄²⁻, 10 µM Fe, 10 µM Mn, 5 µM Zn, 0.8 µM Cu, 20 µM B, and 0.5 µM Mo. The recommended EC in the root zone of soilless melon crops is 2.9 dS m⁻¹, but values of up to 3.2 dS m⁻¹, particularly during fruit ripening, may be beneficial in terms of fruit quality.

Zucchini

Zucchini squash (*Cucurbita pepo* L.) is an important plant in many Mediterranean countries for out-of-season greenhouse production and is successfully cultivated in soilless culture systems. Its nutrient requirements are similar to those of cucumber, with minor differences related to their metallic macrocation and boron requirements. In particular, zucchini has somewhat smaller requirements for K

and Ca, but a higher demand for Mg. In contrast, the B requirements of zucchini are lower than those of cucumber. Furthermore, as with cucumber, the supply of Si through the nutrient solution is beneficial for zucchini, particularly when plants are exposed to salinity and other types of abiotic stress, or when there is a risk of powdery mildew attacks.

Zucchini squash was found to be moderately sensitive to salinity under Mediterranean climatic conditions (Rouphael *et al.*, 2006). Accordingly, EC values in the root-zone solution ranging from 2.6 to 2.8 dS m⁻¹ are considered optimal for soilless zucchini squash grown in Mediterranean greenhouses. Nevertheless, if the concentrations of Na, Cl, and/or Ca in the available irrigation water are substantially higher than the optimal levels, an accordingly higher EC in the root zone of zucchini squash must be accepted to avoid shortages in nutrient supply. Nutrient solution compositions for zucchini squash crops grown under Mediterranean climatic conditions are given in Table 10.

TABLE 10

Recommended EC (dS m⁻¹), pH and nutrient concentrations (mmol litre⁻¹) in nutrient solutions (NS) ^a for soilless zucchini grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS ^b	SSCS ^c	RE ^d	SSOS	SSCS	RE
EC	2.40	2.20	1.80	2.60	2.00	1.70	2.80
pH	5.60	5.60	-	5.50–6.50	5.60	-	5.50–6.50
[K ⁺]	6.00	5.60	5.30	6.40	6.60	6.10	7.00
[Ca ²⁺]	4.60	4.00	2.65	5.80	3.00	2.10	5.80
[Mg ²⁺]	2.60	2.10	1.50	3.00	1.70	1.20	3.20
[NH ₄ ⁺]	0.70	1.30	1.60	< 0.60	1.20	1.50	< 0.40
[SO ₄ ²⁻]	2.00	1.35	1.00	2.50	1.10	1.00	2.80
[NO ₃ ⁻]	15.50	14.65	11.65	17.30	13.30	10.70	17.50
[H ₂ PO ₄ ⁻]	1.10	1.25	1.05	1.00	1.20	1.00	1.10
[Fe]	20.00	15.00	12.00	25.00	15.00	14.00	25.00
[Mn]	12.00	10.00	10.00	8.00	10.00	10.00	7.00
[Zn]	6.00	5.00	5.00	7.00	5.00	5.00	8.00
[Cu]	1.00	1.00	1.00	1.20	1.00	1.00	1.30
[B]	45.00	35.00	30.00	60.00	35.00	30.00	60.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

Bean

Bean (*Phaseolus vulgaris* L.) is a fruiting vegetable and is cultivated in soilless culture systems. The recommended density is 10–14 plants m⁻², when liquid hydroponic systems or substrate culture are applied. Plants can be supported either by plastic twine attached on a horizontal wire, similar to those used in greenhouse crops of other fruiting vegetables (e.g. tomatoes, cucumbers and pepper), or by stretching suitable nets along the planting lines.

Bean is sensitive to salinity. Therefore, the recommended EC values for nutrient solutions supplied to hydroponically grown bean are relatively low (≤ 2 dS m⁻¹). Furthermore, care should be taken to avoid accumulation of Na⁺ and Cl⁻ ions in the root zone, especially when the nutrient solution is recycled. Given bean's high sensitivity to salinity, the availability of good quality water is essential for cultivation in closed soilless culture systems. Low pH levels in the root zone have a negative impact on plant growth: the pH should never be allowed to fall below 5.5. To avoid excessively low pH in the root zone, the percentage of NH₄-N/total-N in nutrient solutions supplied to bean should be relatively low (< 10%). Recommended compositions of nutrient solutions for bean crops originating from Savvas (2012) are given in Table 11.

TABLE 11

Recommended EC (dS m⁻¹), pH and nutrient concentrations (mmol litre⁻¹) in nutrient solutions (NS)^a for soilless bean grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	Vegetative stage			Reproductive stage		
		SSOS ^b	SSCS ^c	RE ^d	SSOS	SSCS	RE
EC	2.20	2.00	1.60	2.40	1.80	1.50	2.60
pH	5.70	5.60	-	5.70–6.50	5.60	-	5.70–6.50
[K ⁺]	5.40	5.30	4.80	5.80	5.80	5.60	6.40
[Ca ²⁺]	4.60	3.75	2.50	5.60	3.00	1.90	5.70
[Mg ²⁺]	2.00	1.60	1.00	2.50	1.20	0.85	2.60
[NH ₄ ⁺]	0.50	1.20	1.40	<0.5	1.00	1.20	<0.3
[SO ₄ ²⁻]	2.00	1.45	0.90	2.60	1.45	0.80	2.90
[NO ₃ ⁻]	13.50	12.60	9.90	15.00	10.60	9.20	15.30
[H ₂ PO ₄ ⁻]	1.10	1.20	1.00	1.00	1.20	1.00	1.00
[Fe]	15.00	15.00	12.00	15.00	12.00	10.00	15.00
[Mn]	6.00	7.00	5.00	5.00	10.00	5.00	5.00
[Zn]	6.00	5.00	4.00	7.00	5.00	4.00	7.00
[Cu]	0.70	0.70	0.60	1.00	0.80	0.60	1.00
[B]	30.00	20.00	20.00	40.00	20.00	20.00	40.00
[Mo]	0.50	0.50	0.50	-	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

Once over-harvested vegetables

This category comprises leafy vegetables, such as lettuce, rocket and other salad crops, but also kohlrabi, endive, spinach etc. Literature sometimes categorizes crops as transplanted and sowing plants. The general characteristics are:

- relatively high plant density per m² (10–20 for lettuce, > 100 for spinach); and
- short cultivation period (1–4 months).

Common practice is to raise seedlings in pressed peat cubes or pots or in mineral wool cubes. At present, only a small number of enterprises produce leafy vegetables in soilless culture systems in Europe, due to the tough competition from outdoor production and the relatively high investment needed; the economic efficiency is thus questioned (Van Os *et al.*, 2008).

Lettuce

Due to its very short cultivation period, lettuce can be produced in more than eight cropping cycles per year in greenhouses, when grown hydroponically. For soilless cultivation of lettuce, float systems and systems based on continuous nutrient solution recirculation (e.g. NFT) are widespread; cultivation on substrates is less common. Lettuce is characterized by high K and P uptake rates, but is susceptible to Mn toxicity. It is crucial to maintain low nitrate content in the edible tissues: with soilless culture systems it is possible to properly adjust the supply of nitrates via the nutrient solution shortly before harvesting (Schnitzler and Gruda, 2002). In Table 12, recommendations are given regarding the concentrations of essential

TABLE 12

Recommended EC (dS m⁻¹), pH and nutrient concentrations (mmol litre⁻¹) in nutrient solutions (NS) ^a for soilless lettuce grown under Mediterranean climatic conditions

Desired characteristics	Initially applied NS	SSOS ^b	SSCS ^c	RE ^d
EC	2.50	2.40	2.30	2.60
pH	5.60	5.60	-	5.60–6.50
[K ⁺]	7.50	8.00	9.00	6.20
[Ca ²⁺]	5.40	4.80	3.75	7.30
[Mg ²⁺]	1.50	1.10	1.00	1.60
[NH ₄ ⁺]	0.80	1.30	1.60	< 0.6
[SO ₄ ²⁻]	1.50	1.40	1.15	2.00
[NO ₃ ⁻]	17.20	16.40	15.50	18.00
[H ₂ PO ₄ ⁻]	1.40	1.40	1.80	1.20
[Fe]	40.00	35.00	30.00	40.00
[Mn]	5.00	5.00	5.00	1.00
[Zn]	5.00	5.00	4.00	5.00
[Cu]	0.80	0.80	1.00	0.80
[B]	40.00	30.00	30.00	50.00
[Mo]	0.50	0.50	0.50	-

^a The initially applied NS is that used to moisten the substrate or introduced to water culture systems before planting.

^b SSOS: solution supplied to open systems.

^c SSCS: solution supplied to closed systems.

^d RE: target concentrations in the root environment.

Savvas, 2012

nutrients in nutrient solutions for lettuce crops grown in open and closed soilless systems as well as the target concentrations in the root zone.

Other edible crops

In general, it is possible to produce several other edible crops in soilless culture systems, but the cultivated area in Mediterranean countries is not extensive and, consequently, experience with such plants is limited. Nevertheless, some crops (e.g. kohlrabi, radish, endive, spinach, rocket and lamb's lettuces) are successfully produced in this area as well. The most common methods are similar to those applied for lettuce production: flat hydroponic systems, float systems and NFT. The suggested EC level is lower in comparison to lettuce (about 1.3 and 1.6 dS m⁻¹ for kohlrabi and lamb's lettuces, respectively). However, the Fe content in the nutrient solution should be higher than that suggested for lettuce, particularly in lamb's lettuce crops. Values of 4 mg per litre of Fe are, therefore, recommended (Göhler and Molitor, 2002).

OUTLOOK

Although in recent decades numerous scientific papers have addressed various aspects of soilless cultivation under Mediterranean climatic conditions, only a few have focused on the systematic determination of nutrient uptake. Thus, the currently available research data are still incomplete for the establishment of nutrient solution recipes, specifically for Mediterranean climatic conditions. Accordingly, more research is needed in the near future to estimate nutrient and water requirements of soilless cultivated plants under mild winter and dry summer conditions, such as those prevailing in the Mediterranean Basin. Such data would be particularly useful for establishing nutrient solution compositions for closed or semi-closed soilless crops (Savvas, 2002), where accuracy in nutrient-to-water supply ratios is much more important than in open systems for minimizing both ion accumulation in the root zone and discharge of drainage solution.

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13. Quality of planting materials

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INTRODUCTION

Use of high quality planting materials is critical for success in greenhouse plant production. Good propagation capacity must develop together with expanding greenhouse crop production. Some farmers grow their own transplants, while others purchase them from a specialized nursery. When and where to get planting materials must be identified before planning greenhouse production. Proximity to nurseries which might supply transplants is a factor in the site selection of greenhouse production facilities: a long distance from the supplier may preclude the purchasing of transplants. The supply of planting materials (seeds and transplants) must be precisely scheduled for each production cycle. Good coordination skills are required to effectively work with nurseries, especially commercial nurseries, as timing of production and timely delivery of transplants are critical. Whether transplants are produced in-house or purchased from commercial nurseries, care must be taken to follow good agricultural practices to avoid introducing diseases and pests to the production greenhouse through seeds and transplants.

A good transplant is usually defined by the grower's specifications. According to the grower's preferences, different management techniques may be required. For example, home gardeners may favour robust, succulent plants, while commercial farmers may select more hardened plants. No simple procedure can be followed in growing vegetable transplants, and only through experience can you begin to produce a consistent product. In general, vegetable transplants should be stocky, green and pest-free with a well-developed root system. Once transplanted, they should tolerate environmental challenges and continue growing to achieve optimum yield. Overly hardened or underfertilized transplants may not establish quickly, resulting in delayed maturity and reduced yields. Insufficiently hardened or over-fertilized plants may succumb to disease or abiotic stresses. The ideal technique for growing transplants is to raise the plant from start to finish by slow, steady, uninterrupted growth and with minimal stress. Since ideal growing conditions rarely exist, plant growth needs to be controlled through the manipulation of water, temperature and fertilizer.

SEEDS

Potential seed problems are: unexpected low germination rate, contamination with different species and introduction of seed-borne diseases. For example, bacterial canker of tomato (*Clavibacter michiganensis* subsp. *michiganensis*) is a notorious seed-borne pathogen and outbreaks occur annually in tomato production areas worldwide (ASTA, 2009). For early detection, attention must be paid to the seed source as well as to the seedlings during propagation.

Seed source

- Keep records with key information: purchase date, source (vendor name), variety name, seed lot number, seed treatments and other seed quality parameters.
- Test the germination rate before planting: it is recommended to follow the standardized protocol used by the country's organization relevant to seed quality and trade; the germination rate must be recorded and kept with the other seed-related information for potential future track-back needs.
- Use seeds from a reliable source: this is the only way to avoid unintentionally buying adulterated or "fake" seeds or improperly disinfested (therefore contaminated) seeds.
- For genetically modified organisms, follow the relevant national or international regulations.

Handling seeds

Seed storage

Understand seed type. Seeds may be classified according to their tolerance level to drying or temperature: orthodox, recalcitrant and intermediate. Most greenhouse-grown species produce orthodox seeds. However, under similar storage and harvest conditions, seeds exhibit different inherent longevities depending on the species (Walters and Towill, 2004). Relative life expectancy under favourable storage conditions for certain crop groups is: legumes (beans) 3–4 years; crucifers (broccoli, cauliflower) 4–5 years; lettuce, endive and chicory 4–5 years; spinach, beets, carrots and chard 2–3 years; cucurbits (melons, squash) 4–5 years; tomatoes 4 years; peppers 2 years; onion, parsley, parsnip and salsify 1 year. As seeds age, the germination percentage declines at varying rates depending on conditions and species. Guidelines for storage behaviour (orthodox vs recalcitrant) are presented in Table 1.

Store unused seeds following recommendations from the seed source. In general, orthodox seeds should be stored in dark, dry and low temperature environments, kept in a tight container to avoid moisture. When old seeds are used, a germination test must be performed to verify the germination rate; their viability depends on the type of crop. The rate of seed deterioration depends on the type of seed and on the storage conditions. High moisture content and high

TABLE 1
Guidelines to identify storage behaviour of seeds

Trait	Guideline	Some exceptions
Growth habit	Most herbaceous plants produce orthodox seeds.	Aquatic species
Habitat	Many aquatic species, tropical rainforest species, and temperate climax forest species produce recalcitrant seeds.	Most native Hawaiian species, temperate conifers, some maples
Water content at harvest	Most orthodox seeds naturally dry on the parent plant.	All immature seeds, Solanaceae, Cucurbitae
Seed size	Recalcitrant seeds are often large.	Some aquatic species, Rutaceae, some Rubiaceae
Desiccation sensitivity	Orthodox seeds can survive complete water loss; recalcitrant seeds cannot.	Orthodox seeds dried very slowly (for > 2 weeks) can be severely damaged

Walters and Towill, 2004

TABLE 2
Recommendations for relative humidity (RH) and moisture content, together with approximate longevity of selected species

Species	Optimum RH	Optimum moisture content of seed (g H ₂ O / g dw)	Time to 50% loss in viability
Lettuce (<i>Lactuca sativa</i>)	20%	0.04–0.05	>4 years at 5°C >20 years at -18°C
Onion (<i>Allium cepa</i>)	20%	0.06–0.08	>4 years at 5°C >20 years at -18°C
Sunflower (<i>Helianthus annuus</i>)	20%	0.03–0.04	>6 years at 5°C >25 years at -18°C
Pea (<i>Pisum sativum</i>)	20%	0.09–0.12	>10 years at 5°C >25 years at -18°C
Tomato (<i>Lycopersicon esculentum</i>)	20%	0.05–0.06	>12 years at 5°C >25 years at -18°C

Walters and Towill, 2004

temperature will result in a very rapid decline in visibility. Therefore, the longer the seed storage period, the more important that the seed moisture content is low, and that the temperature is also low. The optimum storage humidity conditions and moisture content of seeds of some greenhouse-grown crop species are shown in Table 2.

Avoid using seeds beyond the expected storage life

Seed treatment

Seed treatments vary depending on the seed company. Seed priming can improve germination and emergence, resulting in better uniformity; indeed, seeds of some species are almost always primed, as germination is poor without. Pelletizing seeds produces better uniformity and improves handling in automated seeders.

Germination

- Keep germination facilities clean and free from algae and pests.
- Select conditions optimal for the crop species, thus improving uniformity and minimizing the time, reducing the overall costs for producing transplants.
- Some species require oscillating temperature: eggplant and their rootstocks *torvum* generally germinate faster under day-night oscillating temperature conditions.
- Monitor the media (not air) temperature during germination and control it in the optimum range; evaporation from wet media can reduce the temperature to a few degrees below the air temperature.

GAPs for obtaining and handling seeds

- Keep records of key information.
- Test germination rate before planting.
- Use seeds from a reliable source.
- For genetically modified organisms, follow the relevant national or international regulations.
- Understand seed type for storage and store unused seeds following recommendations from the seed source.
- Avoid using seeds stored beyond the expected storage life.
- Work with seed companies regarding the available options on seed treatments.
- Keep germination facilities clean and free from algae and pests.
- Select germination conditions optimal for the crop species.
- Monitor the media temperature (not air temperature) during germination and control it in the optimum range.

TRANSPLANTS

For greenhouse crop production, it is recommended to use high-quality transplants with the following characteristics:

- absence of infection from diseases or pests
- ability to survive in unfavourable environments after transplanting
- good morphology suitable for planting
- well-developed root system (or higher root to shoot ratio)
- absence of visual defects such as chlorosis (yellowing) or necrosis (dead tissue)

The most important characteristic is disease-free and pest-free status (Doolan *et al.*, 1999).

Organizational separation of transplant production from final crop production is a recent worldwide trend, especially for vegetable and floriculture/ornamental crops requiring special techniques, such as grafting or vegetative propagation, and specific facilities to produce desirable transplants (Plates 1 and 2). It is cheaper to buy such transplants than to produce them in-house, considering all the specialized facilities and skill-sets required. The decision needs to be made by each individual operation, considering all the relevant issues and cost analyses.

When commercial nurseries are not available, or purchasing transplants is not economically advantageous, growers choose to produce their own transplants using their own facilities. Environmental conditions and fertilizer requirements are often specific to transplant production. Transplants are often produced by a short cycle, and growth and development are subject to weather conditions. Good production planning is necessary to coordinate with the final crop production. Records should be kept, including seeding date, variety name, substrate name, tray type, chemicals applied etc.

It is important to avoid wetting foliage. Subirrigation works better than overhead irrigation if the facility is available. If overhead irrigation is the only



Plate 1
Tomato transplants ready for shipping



Plate 2
Tomato grafting operation in Spain (Almería)

option, it is recommended to allow foliage to dry before the sun sets, as prolonged leaf wetness can lead to increased disease development (ASTA, 2009).

Inspections should be carried out to identify signs of diseases and pests. If plants exhibit signs of infection, they must be discarded or an appropriate control method applied.

Grafted seedlings

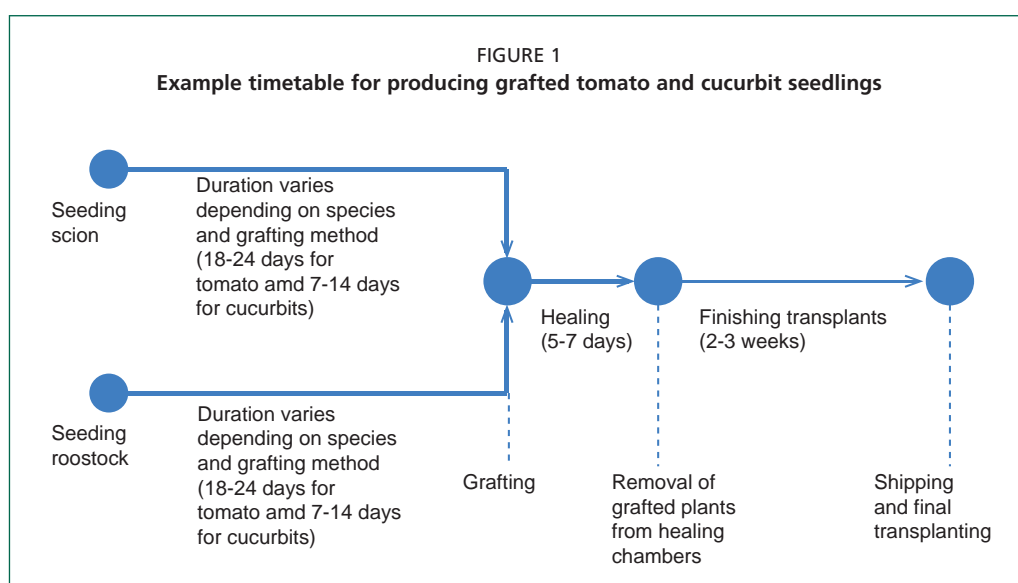
Grafting is widely applied in vegetable production. In some countries, the technology is relatively new and care must be taken to avoid failure or transmission of diseases during the grafting process.

- Keep grafting tools (razorblade, grafting tubes etc.) and working area clean with regular disinfestation. According to ASTA (2009), ethanol (70–75%) and other disinfectants are suitable for disinfecting cutting tools and hands, which should then be rinsed with clean water to avoid damage to the plant from residual disinfectant. Both disinfectants and rinsing water should be changed regularly.
- Choose the rootstock on the basis of the specific problems to be solved by grafting and the grafting compatibility between scion and rootstock. Seed companies have information on expected phenotypes including disease resistance, but it is recommended to test any new scion-rootstock combination on a small scale before starting propagation on a large scale. Table 3 presents guidelines for selecting rootstocks.

TABLE 3
Guidelines for selecting grafting rootstocks

Type	Resistance	Other traits
<i>Tomato</i>		
Interspecific hybrid (hybrid between different tomato species, e.g. 'Maxifort', <i>Solanum lycopersicum</i> x <i>S. habrochaitaes</i>)	Different for different rootstock varieties but generally include <i>Fusarium</i> , <i>Verticillium</i> wilt, root knot nematodes. Some include bacterial wilt and higher race (race 3) of <i>Fusarium</i> .	Generally vigorous. Some rootstocks have chilling tolerance. However, less uniformity in plant growth at the seedling stage (germination and emergency).
Intraspecific hybrid (hybrid within the same cultivated tomato species, e.g. 'Aloha', <i>Solanum lycopersicum</i>)	Different for different rootstock varieties but generally include <i>Fusarium</i> , <i>Verticillium</i> wilt, root knot nematodes. Some include bacterial wilt and higher race (race 3) of <i>Fusarium</i> .	Very uniform growth. Less vigorous.
<i>Cucurbits</i>		
Interspecific hybrid squash (hybrid between different squash species, e.g. 'Tetsukabuto', <i>Cucurbita maxima</i> x <i>C. moschata</i>)	<i>Fusarium</i> . Some also have vine decline, <i>Verticillium</i> wilt and anthracnose.	Suitable for all cucurbits. Traits varied among different rootstock varieties (vigour, chilling heat or drought tolerance etc.).
Bottle gourd (<i>Lagenaria siceraria</i>)	<i>Fusarium</i> . Some also have resistance to vine decline, <i>Verticillium</i> wilt and anthracnose.	For watermelon. Chilling tolerance.
Fig leaf gourd (<i>Cucurbita ficifolia</i>)	<i>Fusarium</i>	For cucumber. Chilling tolerance.

- Select the optimum grafting method on the basis of plant performance after grafting and success rate of grafting. Tube grafting is a standard procedure for tomato and eggplant, but there are several grafting methods used for cucurbits. When considering automated grafting, it is important to take into account the advantages (e.g. lower labour input) and challenges (high capital costs and limited flexibility in terms of size of plants or trays).
- Prepare scion and rootstocks to reach optimum graftable stage at the same time. Depending on the grafting method and species to graft, grafting must be done at the optimum growth stage of scion and rootstock seedlings. Use of overgrown or too young seedlings beyond optimal ranges reduces the grafting success rate. Good propagators must pay attention to seed germination timing and growing conditions to produce scion and rootstock seedlings at an optimal stage for grafting. An example of a propagation timetable is shown in Figure 1.
- Keep healing facilities clean and free from algae and pests. Healing conditions often include high humidity (nearly 100%) and warmth (28–29 °C) with lighting, conducive to the growth of algae and fungi and the rapid spread of disease.
- Choose between two-headed and single-headed grafted seedlings. For tomato, two-headed seedlings (pinched to induce two lateral shoots) are widely used to reduce the number of plants needed per cultivation area. However, an inappropriate combination of scion and rootstock may reduce the yield when they are two-headed. A small test to determine growth and yield capacity of two-headed plants must be conducted before using them on a large scale.



GAPs specific to the grafting of seedlings

- Keep grafting tools (razorblade, grafting tubes etc.) and working area clean.
- Proceed with the disinfection of the grafting tools between each cut with ethanol (70–75%) or other suitable disinfectants.
- Choose appropriate rootstock.
- Choose optimum grafting method.
- Prepare scion and rootstocks to reach optimum graftable stage at the same time.
- Keep healing facilities clean and free from algae and pests.
- Carefully decide whether to use two-headed or single-headed grafted seedlings.

Purchasing transplants from commercial nurseries

- Use transplants from reliable nurseries. Long-distance transportation causes deterioration of transplant quality. Select nurseries not only for their propagation skills (product quality) but also for their proximity to the production site and the transportation methods used.
- Upon receipt of transplants, inspect carefully for signs of disease or pests. On finding signs of infection of notorious diseases and pests that could spread in the greenhouse (e.g. bacterial canker or TYLCV for tomato, bacterial fruit blotch for cucurbits), discard all the transplants and disinfect any trays and bench surfaces with which they have come into contact.
- Maintain records of any products used for controlling pests and diseases during the propagation period.
- For genetically modified organisms, follow the relevant national or international regulations.
- If possible, visit the nursery during the transplant production process, check the young plants and discuss the quality with the manager.

Production scheduling

In commercial propagation, production scheduling is critical to maximize profits.

- Schedule backwards, starting from the target shipping (delivery) window determined by customers or final crop production schedule. The time required to reach the growth stage suitable for transplanting is largely dependent on the crop species, climate conditions (solar radiation, day and night air temperature, and CO₂ concentration) and growing methods (substrate, fertilizer and tray types). Experience is required to forecast transplant finishing time.
- Understand the different facility requirements for the various stages of transplant production. For standard transplants, there are several stages, such as germination, transplanting, hardening and shipping. For grafted seedlings, there may also be sorting, grafting, healing and pinching. It is first necessary

to establish how many trays (flats) one germination room can hold and how many workers are available for grafting in a given week.

- Understand two variables: crop time and production space. Scheduling production and analysing facility use associated with transplant production can be a complicated process comprising multiple variables. To better schedule crops and turns, nursery propagators must develop their own computerized spreadsheets to better understand the facility use in any given week of the production period. This capacity is extremely important when propagation involves multiple species and different finishing timings.

Packing and transportation

- Select the packing and transportation method. Transplants are best transported when packed in trays inside cardboard boxes or on racks in trailers, but some growers prefer to receive “pull-and-pack” seedlings to reduce transportation costs. In either case, packing to accommodate rough handling is necessary, especially when a commercial freight service is employed (Plate 3).
- Avoid long distance transportation. Transplants should be transported over the shortest distance possible, to minimize costs as well as the damage associated with transportation. However, in some cases, such as grafted seedlings that are not widely available in some countries, transportation may be longer than the normal time for vegetable transplants. Normal transportation time is no longer than 10 hours.
- Select the timing of transportation to minimize environmental stress. Once scheduled, select exact timing to avoid the risk of exposing transplants to extreme heat or cold. During summer, overnight or early in the morning is preferable to midday to avoid heat stress, especially when plants are transported in a non-refrigerated truck. In contrast, midday transportation is more desirable when freezing temperatures are expected at night.
- Select the transportation route to minimize mechanical stress. Mechanical stress caused by vibration during transportation has a negative impact on the



Plate 3

Rough transportation or handling of boxes could result in tumbled seedlings during transportation



Plate 4

Ventilated truck used for transporting seedlings

transplants. It can physically damage the transplants or promote ethylene production. Ethylene accumulation can induce adverse physiological impacts such as flower abortion or leaf yellowing, especially during long distance transportation.

- Use a refrigerated trailer at a controlled selected temperature for long distance transportation. Too high temperatures can produce adverse physiological effects such as flower abortion (Kubota and Kroegel, 2006).
- Assure ventilation to avoid ethylene accumulation during transportation. Plate 4 shows a commercial nursery truck (non-refrigerated) designed for transporting transplants. This type of truck has some ventilation and is suitable for relatively short distances (no more than several hours).
- Complete necessary importation paperwork for international shipping of transplants.
- Do not transport plants if there is any sign of disease or virus infection. Introduction of viruses such as TYLCV is often associated with transportation of plant materials. Accidental introduction of infected plants following inappropriate judgment by a careless propagator could cause a catastrophic outbreak affecting the entire production region.

FACILITIES AND MATERIALS TO GROW PLANTS

The facilities and climate conditions for transplants are different from those for final crop production. Young seedlings are generally more sensitive to abiotic and biotic environmental stresses and a growing facility must be carefully selected in order to achieve optimum growing conditions. There are several production stages, and each one has specific recommendations with regard to environmental conditions, fertilization and plant maintenance methods.

Production site selection

The transplant production facility should be located at a distance from the farming area, which is a potential source of insects and diseases that can easily reach the transplant production facility. The site should be levelled and well drained with ready access to an abundant supply of quality water. The greenhouse should be positioned sufficiently far from surrounding trees or buildings so as to prevent shadows. Considerations concerning greenhouse location may be summarized as follows:

- good drainage and water supply
- sufficient distance from cultivation area
- good proximity to shipping routes
- easy access to utilities
- local zoning for land use and tax laws
- room for expansion and absence of shadows

Seedling trays

Seeds can be sown in a variety of ways (depending on their end use) in individual plant containers or plastic flats filled with various types of sterile growing media (substrates).

Choose trays or containers suitable for the production (Plate 5). Criteria include plant species, growing conditions (irrigation method), local availability and type of mechanical seeder used. There are various containers and trays:

- Individual containers may be more appropriate for foliage plants or mature seedlings (flowering stage) of vegetable species. They come in paper, plastic, clay, peat moss, Styrofoam (Plate 6) etc.
- Individual plastic containers (called net pots or web pots) are used in floating or NFT hydroponic systems, filled with coarse substrates, such as perlite, clay pellets and rockwool.
- Moulded plastic or Styrofoam “plug” or cavity (multi-celled) trays are available in various sizes containing tens to hundreds of cavities, and can be filled with growing medium or cubes for the production of multiple seedlings in each tray.

Use steam or other disinfectants to sterilize reused trays. Plastic containers can be sterilized using 10 percent bleach, while Styrofoam containers and trays are steam-sterilized. In some countries in Europe, Styrofoam is recycled to be used for other purposes (Styer and Koranski, 1997). When disinfectant solution is used, soak the trays long enough to ensure efficacy; rinse containers thoroughly to avoid chemical toxicity; allow the trays to dry prior to use.

Choose tray type and size adaptable to the mechanical seeder, transplanter and other greenhouse propagation systems (benches and irrigation systems). Test candidate trays for plant performance as plant growth is affected by type of trays (cell size, volume, colour etc.).

Limit the maximum reuse of seedling trays (or plug trays) to 2–3 times. Styer and Koranski (1997) suggest that the cost of labour for washing, disinfecting,



Plate 5
Seedling trays with various cell shapes and sizes



Plate 6
Tomato seedlings grown in a Styrofoam tray

stacking and storing used trays almost equals the cost of new trays. Reuse also increases the risk of disease introduction resulting from incomplete disinfection.

Substrate¹

- Select a substrate and understand its physical properties. There are various substrates available for horticultural use (e.g. sand, peat, moss, vermiculite, perlite, rockwool, rice hulls, coconut coir, compost). In general, a substrate needs to have good air porosity and water-holding capacity.
- Maintain the media pH in the optimum range (5.5–6.5 in general). Too high or too low pH can cause micronutrient deficiency or toxicity, respectively.
- Keep the initial level of EC (electrical conductivity) below 0.75 dS/cm at a 2:1 (v:v) dilution (Styer and Koranski, 1997). Some substrates have fertilizers mixed in (known as “starter charge”) and the amount of starter charge needs to be taken into account in the fertilization schedule.
- Use substrate from a reliable source. Organic substrates (e.g. coconut coir) are often inconsistent in quality and vary depending on the source and origins.

Chemicals

- Ensure that any chemicals used during propagation do not violate the regulations of the country where the plants are to be grown for production.
- Use products from reliable sources.
- Follow the application instructions on the product label; some chemicals require professional certificates for applicators (workers).
- Keep records of product name, dose, application method, operator name, date and time of application etc.

Fertilizers

- Use products from a reliable source; avoid low quality fertilizers as they may contain contaminants such as heavy metal.
- Keep good records when mixing fertilizers to make up stock nutrient solution. Record fertilizer product name, salt name, weighed amount, operator name, date and time etc.
- Check EC and pH of nutrient solution regularly; EC and pH meters need to be calibrated and maintained using methods recommended by manufacturers.
- Use appropriate nitrogen source based on plant performance, pH requirement and costs. For example, use of nitrogen in nitrate form at a higher ratio tends to keep the substrate more basic.

¹ For more information concerning substrates, see chapter 11.

- Handle acid and base used for pH control cautiously with appropriate worker protection equipment (safety goggles and gloves). Store them in an appropriately designated acid cabinet.

Seeding machine and automation

Choose the seeding machine and other automation (tray filler etc.) on the basis of expected use and performance, as it could be a significant capital investment. Types of seed (size, coating and shape), trays (dimension, number of cells) and substrate need to be considered in order to select the best performing machine.

IPM facility

In order to reduce the risk of introduction into the greenhouse of insect pests or insect-transmitted viruses, it is recommended to:²

- use a double-door entrance;
- cover the air intake (vents) with insect screens;
- control weeds inside and outside.

IRRIGATION AND FERTIGATION

Irrigation

It is important to choose an appropriate irrigation method or system, taking account of the relative advantages and disadvantages. There are two basic irrigation systems for transplant production:

- Overhead irrigation systems are traditionally used for containerized transplants (Plate 7). However, they can contribute to pathogen attack when used in regions with high temperatures and humidity.
- Subirrigation systems (flotation or ebb and flow) are designed to flood beds with nutrient solution. In subirrigation, the water must contain disinfectants and algae growth protectants.

The advantages of subirrigation include lower pesticide, water and fertilizer use in propagation, elimination of groundwater contamination, and reduced risk of foliar and soil-borne diseases (Thomas, 1993). Also, overhead watering does not guarantee uniform waterflow throughout the medium and can induce drought stress in the roots, especially during hot seasons. Overhead



Plate 7
Overhead irrigation used for transplant production facility

² For the design or installation criteria and specifications of each facility, refer to chapter 15. To understand the possible impact of insect screens on greenhouse ventilation, refer to chapter 3.

irrigation enhances root growth, but it uses more fertilizer than subirrigation (Nicola and Cantliffe, 1996).

To improve fertilizer and water-use efficiency, over-irrigation should be avoided. Transplant quality tends to be low (stem extension or tender tissue) when grown under conditions of over-irrigation. It is important to water transplants thoroughly until the entire substrate is moist, and then allow the substrate water content to reduce before the next watering. When overhead irrigation is used, late afternoon watering should be avoided as the plants remain wet overnight, increasing the likelihood of disease. A too-wet substrate also increases the incidence of damping-off disease.

Fertigation

Choose the fertilizer concentration, frequency and dose according to plant growth stage and climate conditions (solar radiation and temperature, which influence transpiration demand). For example, target concentrations for fertigation in the solution for tomato seedlings are 80–100 mg/litre total nitrogen (75–100% in nitrate form), 30–50 mg/litre phosphorus, 140–180 mg/litre potassium, 100–150 mg/litre calcium and 30–60 mg/litre magnesium, in addition to other micronutrients. The pH is normally adjusted to 5.5–6.5. Seedlings grown on high rates of nitrogen fertilization are succulent and less resistant to dry weather and solar radiation, leading to a low rate of plant survival after transplanting in the open field (Rosca, 2008). Transplant quality can be improved by applying higher concentrations of fertilizer less frequently (known as “pulse feeding” – Garton *et al.*, 1994), resulting in thicker stem diameters. Limiting fertilizer is also used to harden transplants before shipping or transplanting. Carefully monitor the discharge (amount and EC) to minimize pollution. Direct discharge to the ground should be avoided as it contaminates the groundwater.

GROWTH CONTROL AND HARDENING TECHNIQUES

Hardening is a crucial step in transplant production. In general, transplants should have well-balanced shoot and root development. Young seedlings growing at high planting densities may have extended stems or excessively large shoot mass relative to the roots. Spindly tender plants are more vulnerable to mechanical damage during handling and transplanting. The quality of transplants affects stand establishment after transplanting to the final production greenhouse. Hardening preconditions transplants to tolerate transplanting stress by exposing them to, for example, water stress; the practice is usually applied to transplants to be used in open-field production or to be grown in environmental conditions harsher than those they were exposed to during propagation. Excessive hardening should be avoided as it may exhaust the plant's energy reserves (Garton *et al.*, 1994).

A typical hardening method involves restriction of the water supply and gradual exposure to conditions expected in the fields or greenhouse to which the plants

are transplanted (light intensity, day-night temperature oscillation and relative humidity). This hardening process is performed over several days or for over a week, depending on the species and preferred nursery practice. Some vegetable seedlings (e.g. tomato) may also be hardened off with limited fertilization, as too much fertilization, especially nitrogen, tends to make seedlings soft. Some growers move the seedling trays to benches placed in open field in direct sunlight. However, it is recommended that transplants used for greenhouse production be hardened off inside the greenhouse to mitigate the risk of bringing in insect pests.

Day-night temperature difference (DIF)

Plant stem growth rates of some floricultural and vegetable species are positively correlated to the difference between day temperature (DT) and night temperature (NT), known as DIF ($DIF = DT - NT$) (Moe and Heins, 1990). A high DIF promotes stem elongation and the daily average temperature determines overall development rate (leaf emergence and flower initiation). Using DIF helps to keep the seedlings compact in size without using growth regulators. Keeping transplants cooler during the day than at night reduces plant height in the temperature range 10–30 °C (Wien, 1997). High temperatures during the first 3–4 hours after sunrise can cause considerable elongation in vegetable seedlings (Bodnar and Garton, 1996). This excessive elongation can be mitigated by keeping the greenhouse temperature cooler (by 4–5 °C) during morning hours than at night (Bodnar and Garton, 1996).

Irrigation deficit and water stress

When plants are subjected to mild water stress, the rate of stem elongation and leaf area expansion decreases, and carbohydrates accumulate in the leaves. Water stress therefore induces changes in plant growth that are helpful in preparing the plant for transplanting (Wien, 1997). However, as the plant transpiration rate is affected by environmental conditions, experience is required to determine irrigation timing without imposing too much water stress. A soil moisture sensor calibrated for the specific substrate offers an alternative approach.

Nutrition deficit

The growth rate of transplants can be regulated by controlling the concentration of nitrogen and other nutrients in the substrate. Reducing nutrient supply just before transplanting can slow down the growth rate during the hardening stage. As long as the transplants are not completely starved of the major nutrients by this procedure, there should be little problem with the resumption of growth after transplanting (Wien, 1997).

Shaking and brushing

Mechanical stress affects seedling growth, because it can enhance ethylene production. Brushing the tops of the transplants several times a day can have remarkable dwarfing effects (i.e. shortening stem and petioles; increasing

chlorophyll content) (Wien, 1997). The effects of these mechanical perturbations vary among species and cultivars. Brushing has proved successful in solanaceous crops (including tomato, pepper and eggplant), but care should be taken with cucurbits, which are more fragile and may become damaged (Schrader, 2000).

With tomato, keeping transplant height short results in a reduction of stem elongation rate, especially important during winter, when light conditions are suboptimal (Fontana *et al.*, 2003). Chemical growth regulators may not be used to control vegetable transplant height (it is necessary to check the registration status with the local authority). Therefore, mechanical conditioning is one way of controlling stem elongation in commercial greenhouse production.

Transplant age

When producing vegetable transplants, seedlings should be transplanted at the optimum age. Generally, as the age of the transplant increases, leaf number, height, leaf area and dry shoot weight of vegetable seedlings increase linearly, regardless of transplant cell volume. Avoid any delay in transplanting. Almost all vegetables may be transplanted as early seedlings with little effect on growth, but as they increase in age, this situation changes (Vavrina, 1998). Age strongly influences subsequent performance in the greenhouse. Although planting the largest seedlings possible might appear advantageous in terms of getting the crop off to a quick start, larger seedlings are also more prone to transplanting shock. In general, relatively young vegetable transplants provided with adequate growing space in the greenhouse produce the best stand and fastest crop development. The added stress associated with transplanting larger-than-optimal plants appears to substantially delay crop development.

Determine best growing practices for achieving optimum age of transplants. The optimum age depends on the crop, cell size to be used and conditions during the grow-out period. For example, 2-week-old transplants grown in the small cell volume may be the best option for muskmelon growers if their sole concern is total-season yields. However, if growers want to maximize early-season yields, then 2-week-old transplants grown in the large cell volume are the best choice (Walters *et al.*, 2005). Growers must adjust their growing practices and schedules for different crop species and cell sizes. Table 4 lists general guidelines for transplant production in various crops, planting time and cell sizes.

There is no single definition of the best seedling age or the most appropriate phenological stage of transplant age. In general, northern countries use older and further developed seedlings, as follows (OMAF, 2007):

- Tomatoes: first flowers showing
- Cucumbers: 4–5 true leaves visible
- Peppers: flower at first branching level opening

TABLE 4
Scheduling transplants of various cell sizes, for several vegetable crops

Crop	Tray size ^a	Transplant age and production details
Early-market tomatoes	24, 38, 50	Usually seeded in 288s or 406s and transplanted to large tray at first true leaf; aim for approx. 8-week-old field-ready plants
Mid-season to late tomatoes	128–288	Direct-seed in tray; plants should be 6–7 weeks old for mid-to-late May plantings, 5 weeks old for June plantings
Early peppers	50 or 72	Transplant seedlings or direct-seed in tray; aim for 8–9-week-old field-ready plants
Mid-season to late peppers	128–200	Direct-seed in tray; aim for 7–8-week-old field-ready plants
Early cole crops	72 or 98	Direct-seed in tray; aim for 5–6-week-old field-ready plants
Mid-season to late cole crops	128–200	Direct-seed in tray; aim for 4–5-week-old field-ready plants
Cucumbers, melons, squash	24–128	Direct-seed in tray; aim for 3–4-week-old plant for 24 or 38 trays, 2–3-week-old plant for smaller cells (128 trays)
Spanish onion	200 or 288	Direct-seed in tray; seedlings should be clipped several times to produce a stocky transplant; aim for 8–10-week-old plants

^a Standard cell tray size: 540 x 280 mm.
Bodnar and Garton, 1996

In other countries, tomato seedlings 3–5 weeks old and not yet flowering (Peet and Welles, 2005) are considered ideal, while seedlings over 5 weeks old are less desirable (Zeidan, 2005). While modern cultivars, improved production systems and technical expertise may produce high yields regardless of transplant age, relatively young transplants are still preferred for commercial production under Mediterranean conditions because older seedlings are more costly to produce and difficult to handle.

PHYSIOLOGICAL DISORDERS
Nutrient deficiency and toxicity

- Optimize fertilization programme based on the plant’s needs. Different species require different fertilization. Some commercial substrates for transplant production contain a starter charge of fertilizers, in which case no fertilization is required for the first few days. For nitrogen, many plant species perform better when both ammonium nitrogen and nitrate nitrogen are used. However, an excessively high rate of ammonium nitrogen may cause toxicity to the plants; furthermore, the form of nitrogen also affects the pH in the substrate (nitrate makes it more basic and ammonium more acidic). An example of phosphorus deficiency in tomato plants is shown in Plate 8.

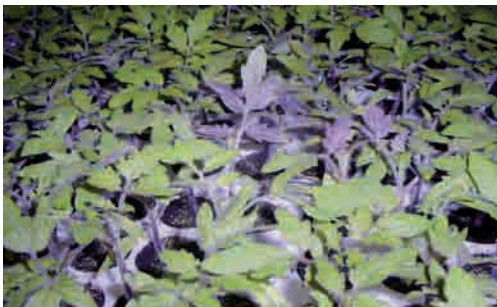


Plate 8
Typical symptom of phosphorus deficiency in tomato – seedlings develop purple pigments (anthocyanins)

- Maintain adequate pH in the substrate to avoid nutrient deficiency and toxicity. Generally, a pH of 5.5–6.5 is considered optimum for many plant species: a too high pH can lead to iron deficiency inducing pale green newly emerged leaves; too low can cause micronutrient toxicity (e.g. boron). Some substrates (e.g. peat moss) are acidic and others (e.g. vermiculite) basic. The amount of bicarbonate ions determines the water alkalinity and influences the buffer capacity of the nutrient solution in the substrate.
- Use fertilizers from a reliable source to avoid contamination (heavy metals etc.).
- Analyse the water quality and design the fertilization programme accordingly. Water quality may change over time (seasons or years), and periodical analysis in a reliable laboratory is therefore recommended. Excessive amounts of sodium, soluble salts or bicarbonates can become problematic and growers may want to consider another water source or different water treatment.

Pests and diseases

Good agricultural practices relevant to plant propagation are described below.

- Inspect planting materials regularly. Early detection is critical to control biological problems and minimize damage. Propagation is usually conducted in short cycles, but because of the high density, pests and diseases spread very rapidly. Once any symptom is found, minimize access to the affected area and notify workers of the outbreak as soon as possible.
- Be familiar with the symptoms of commonly occurring pests and diseases to identify problems at an early stage and minimize plant loss.
- Apply appropriate control methods (chemical or biological) in consultation with a local extension agent or advisor.
- Do not apply foliar fungicides in high temperatures as foliage may get injured.

Disorders caused by growing environments

Pay attention to light contamination from neighbouring greenhouses and buildings at night. Street lights and worker's lights sometimes influence plant morphology and flowering. Be familiar with toxicity symptoms of air contaminants. Incomplete combustion of gases causes air pollution that can harm humans as well as plants. The concentrations that negatively affect plants vary according to whether exposure is short term or long term. Young transplants are especially tender and sensitive to by-products of incomplete combustion (Bodnar and Garton, 1996), and tomato is particularly sensitive to ethylene exposure. Problems are often associated with the first use of heating systems in the winter and they disappear as heating demand becomes less.

TRACEABILITY

Record key information for each lot of planting materials (seeds and transplants) including material information (source, type), dates, facility used, environmental data and workers' names. Consider the introduction of a tracing technology (e.g. barcodes or RFID – radio frequency identification), to identify each lot or tray of transplants (especially if a large number are grown under various schedules in the same facility) and to record the relevant production-related information. The successful introduction and use of such a system significantly reduces errors in boxing and shipping.

GAPs for growing and handling transplants (1)

- Keep records of key information (seeding date, variety name, substrate name, tray type, chemicals applied etc.).
- Choose the appropriate irrigation method/system and carefully manage the irrigation to keep the substrate uniformly wet while avoiding over-irrigation
- Avoid wetting foliage as much as possible.
- Inspect carefully to identify signs of diseases and pests.
- Understand and practise hardening methods.
- Avoid delay in transplanting.
- Optimize fertilization programme based on the plant's needs.
- Inspect planting materials regularly.
- Apply appropriate control methods (chemical or biological).
- Do not apply foliar fungicides in high temperature conditions.
- Be familiar with toxicity symptoms of air contaminants.
- Consider introducing tracing technologies (e.g. barcodes or RFID).
- Maintain records of any products used for controlling pests and diseases during the propagation period.
- Schedule transplant production backwards, starting from the target shipping (delivery) window.
- Understand the different facility requirements for different stages of transplant production.
- Select optimum packing and transportation methods.
- Avoid long distance transportation and select transportation route to minimize mechanical stress.
- Select transportation timing to minimize environmental stress.
- Use refrigerated trailer at a selected temperature for long distance transportation.
- Assure ventilation to avoid ethylene accumulation during transportation.
- Complete necessary importation paperwork for international shipments of transplants.
- If there is any sign of disease or virus infection, DO NOT transport plants.

ORGANIC TRANSPLANT PRODUCTION

Record-keeping

Record-keeping and certification are required for all organic producers selling products labelled “certified organic” (Santos, 2007). Production of organic transplants involves more than using organic fertilizers and substrates or avoiding the use of non-approved pesticides. Regulations extend to greenhouse building materials and phytosanitation methods. In an organic nursery, the use of chemical-synthetic products for substrates and plant protection is not allowed; appropriate cultural techniques and inputs must be adopted to obtain well-established seedlings (Nicola *et al.*, 2011). Root zone management is necessary for the main inputs in the organic nursery: containers, substrates and fertilizers (all organic farming certified).

Containers and substrates

For organic nurseries, biodegradable containers composed of biodegradable polymers are commercially available (Nicola *et al.*, 2010). Organic commercial substrates are composed of peat and other products allowed in organic farming regulations. Peat can be completely substituted using a substrate composed of citrus residues mixed with coconut coir (Possanzini, 2006). New organic substrates that are possible alternatives to peat include: rice hulls or rice chaff (a by-product of rice processing), and *Posidonia oceanica* (L.) Delile (an abundant sea plant) (Sambo and Santamaria, 2009).

Organic farming regulations list the permitted fertilizers (guano, manure, potash, seaweed etc.) (Nicola *et al.*, 2010); most certified organic fertilizers can be used for post-transplant or mature crop production, since they are generally applied in the soil months before being absorbed by the plant during crop development. The problem of using plant- or animal-based fertilizers is finding horticultural and animal residues originating from organic farming. To improve the uptake of organically based soil nutrition, techniques related to mycorrhization could be adopted: through pre-inoculation, the young seedlings benefit from enhanced availability of nutrients, especially those coming from an organic matrix (Conversa *et al.*, 2009).

GAPs specific to organic transplant production

- Keep records of key information.
- Be familiar with materials (trays and substrates) allowed for organic production.

SEEDLING MYCORRHIZATION

Mycorrhization establishes symbiosis between plants and fungi. It can improve not only the growth of seedlings but also their physiological status by enhancing the photosynthetic capacity, and increasing the uptake of water and nutrients and their accumulation in the seedling tissues (Rincón *et al.*, 2005). Environmental conditions characterized by the Mediterranean climate include prolonged dry periods with high temperatures and rain concentrated in a few months. These climatic conditions limit the activity of natural fungal inoculums of soils by reducing the optimal time for fungal spore germination and mycelial growth, thus minimizing the opportunities for root colonization by native fungi. Under these circumstances, controlled nursery inoculation with suitable mycorrhizal fungi can be an advantage for the successful establishment of transplants in Mediterranean regions. Furthermore, water quality in many areas of the region is low due to high salinity: the advantages of mycorrhization include enhancing salinity tolerance (Ruta *et al.*, 2009), enhancing overall plant growth (Conversa *et al.*, 2009), improving product quality (Tiradani and Gianinazzi, 2009; Kappor *et al.*, 2004) and enhancing plant resistance to *Fusarium* and *Phytophthora* (Tiradani and Gianinazzi, 2009).

QUALITY OF PLANTING MATERIALS

Access to high quality planting material is essential for successful greenhouse vegetable crop production. GAPs relative to seeds and transplants are generally classified as follows:

- Prevention of introduction or spread of disease
- Production of high quality seedlings
- Minimization of environmental pollution

GAPs for growing and handling transplants (2)

- Select types of tray/container suitable for the production.
- Use steam or other disinfectants to sterilize reused trays.
- When disinfectant solution is used, soak the trays long enough to ensure efficacy.
- Choose tray type and size adaptable to the mechanical seeder, transplanter, and other greenhouse propagation systems (benches and irrigation systems).
- Limit reuse of seedling trays (or plug trays) to 2–3 times.
- Select substrate and understand its physical properties.
- Keep the media pH and EC for optimum range.
- Use substrate from a reliable source.
- Make sure that the chemicals used during propagation do not violate the country's regulations where the plants are grown for production.

GAPs for growing and handling transplants (2, cont'd))

- Use products from a reliable source.
- Follow chemical application instructions on product label; keep records of product use.
- Check regularly EC and pH of nutrient solution.
- Use appropriate nitrogen source, based on plant performance, pH requirement and costs.
- Handle acid and base used for pH control cautiously with appropriate worker protection equipment.
- Choose the seeding machine and other automation (tray filler etc.) on the basis of expected use and performance.
- Choose fertilizer concentration, frequency and dose according to plant growth stage and climate conditions.
- Carefully monitor the discharge (amount and EC) to minimize pollution.
- Analyse water quality and design fertilization programme accordingly.

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14. Cultural practices

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INTRODUCTION

The Mediterranean region is one of the most important areas in the world in terms of protected cultivation, thanks to its mild winter climatic conditions and the possibility of adopting very simple protective shelters. Vegetable production under protected cultivation is a major agricultural sector in most Mediterranean countries and both cultivated area and production have increased consistently in recent decades. Solanaceous crops (tomato, pepper, eggplant) and cucurbits (cucumber, melon, courgettes, watermelon) now account for more than 80 percent of the protected area (Tuzel and Leonardi, 2010).

There are a wide range of cultural practices of varying importance, but with the common objective of optimizing production value and maximizing economic returns from vegetable production. Most are associated with integrated pest and disease management, particularly in terms of reduction of pesticide use. Some cultural practices – namely plant protection, irrigation and fertilization – are described in detail in separate chapters. The current chapter focuses on cultural practices related to soil preparation, crop establishment, control of growth and fruit-setting during the cropping period, intercropping, mulching and harvesting.

SOIL PREPARATION

Although soilless culture is now a well-established technology for intensive greenhouse cultivation, the majority (96.4%) of greenhouse vegetables produced in Mediterranean countries come from soil-grown crops (Tuzel and Leonardi, 2010). Loamy soils are ideal for vegetable production; however most greenhouses are located in coastal areas of the Mediterranean region where sandy textured soils are more common, characterized by high salinity or pH, and a low level of organic matter and nutrients. Advantages are that they warm up earlier, are easier to till, have better drainage and are never too wet. High yields and good quality of high-value greenhouse vegetables can be achieved with correct soil management and attention to the following practices:

- Increase of organic matter content to improve soil texture and related characteristics, soil chemical properties and cation exchange capacity.

- Control of salinity and alkalinity.
- Provision of adequate and balanced nutrient supply (see chapter 10).
- Control of soil-borne pathogens.

Increasing organic matter content

Nearly 75 percent of the total area in the Mediterranean Basin has low (3.4%) or very low (1.7%) soil organic matter content (Torrento and Oriol, 2002) – a potentially important source of nutrients for plant growth. However, organic matter enrichment is not easy in the Mediterranean region, particularly in greenhouses, owing to the high cost and limited availability of manure, and its rapid mineralization at high temperatures. Application of compost is currently considered to be the most appropriate strategy for compensating annual soil carbon mineralization. However, the supply of 15 tonnes/ha of compost is recommended to reduce the hazards originating from excessive release of nitrates in the soil (Morra *et al.*, 2010).

Improvement of salinity

From an agricultural point of view, salinity is the concentration of dissolved mineral salts in the soil solution and irrigation waters. Most dissolved mineral salts are in the form of cations and anions. The major cations in saline soil solutions are: Na^+ , Ca^{2+} , Mg^{2+} and K^+ , and the major anions: Cl^- , SO_4^{2-} , HCO_3^- and, at very high pH, also CO_3^{2-} . Salinity is a major problem in the Mediterranean region due to low water quality; high fertilization; and overexploitation of groundwater, particularly in coastal areas, resulting in intrusion of seawater in terrestrial groundwater courses. Salt accumulation in the root zone depends on water uptake by plants and evaporation from the soil surface; salt concentration is proportional to the volume of water removed by these processes (Bresler *et al.*, 1982). Salt accumulation can be avoided by irrigating with small volumes; tillage; and mulching to prevent upward movement of saline water from deeper layers (FAO, 1990).

Control of soil-borne pathogens

Soil-borne pathogens can be controlled by soil disinfection: physically, by increasing the soil temperature, or chemically, using fumigants. According to good agricultural practices (GAP), application of chemical treatments for soil disinfection should be avoided as much as possible. With the phasing out of methyl bromide, soil solarization – a non-chemical method to combat soil-borne pathogens – has become an important tool in integrated greenhouse vegetable production and is widely adopted by farmers. Solarization is a process that exploits the greenhouse effect by using transparent plastic materials with the objective of increasing the temperature of the soil for disinfection purposes (Eltez and Tuzel, 1994). The effect of soil solarization can be improved if it is combined with alternative, low toxicity chemicals, biofumigation or the use of grafted seedlings (Tuzel and Özcelik, 2004).

Solarization – GAP recommendations

- Irrigate soil before and during solarization if it becomes dry.
- Place transparent PE (25–30 μ) over soil surface and bury edges without gaps (Plate 1).
- Leave plastic for 4–6 weeks.
- Apply in the summer months (June, July, August) for greatest efficiency.



G. OZTERKING

Plate 1
Soil solarization

PLANTING

Greenhouse crop index and occupation index

The greenhouse crop index is the number of successive crops per year cultivated in the greenhouse. In recent years, it has decreased as a result of better climate control, particularly ventilation and cooling, enabling a longer growing season (Baudoin, 2006). The greenhouse occupation index represents the number of days per year that the greenhouse is effectively occupied by crops. It has reached 0.85, nearing the currently prevailing index of 0.94 in the Netherlands, as a result of improved greenhouse design, cultivation practices and technology use. However, there remains a significant difference in yield between locations (Table 1).

TABLE 1
Cultivation schedule and yield of several crops in different locations of the Mediterranean region and in the Netherlands

	Transplanting	Harvest start	Harvest end	Yield (kg/m ²)
<i>Almeria</i> ^a				
Truss tomato	Aug.	Nov.	June	15
Pepper	July	Oct.	Mar.	7
Cucumber (several cycles)	Aug.–Oct.	Oct.–Dec.	Dec.–Mar.	6–10
<i>Ragusa</i> ^b				
Cherry tomato	Sept.	Nov.	June	6–12
Truss tomato	Oct.	Dec.	April	8–10
Pepper	July	Sept.	Dec.	4–5
	Oct.	Mar.	April	4–6
	Nov.	April	June	6–9
<i>Netherlands</i> ^c				
	(no. weeks)	(no. weeks +/- 2)	(no. weeks, incl.)	
Round tomato	48–50	12	47–50	60
Beef tomato	47–50	12	46–50	60
Truss tomato	47–50	12	47–52 interplant	55
Cherry tomato	48	12	46	32
Red pepper	47–52	12	43–44	26
Green pepper	1–3	12	47–49	32
Yellow pepper	48–53	15	45–50	28
Orange pepper	47–48	12	44–45	25
Cucumber (3 crops/year)	1–2, 23–24, 33–34	7, 26, 36	23, 33, 47	81

^a Cajamar Foundation.

^b C. Leonardi (personal communication).

^c Quantitative information for the Dutch Glasshouse Horticulture 2008–09. Ed. P.C.M. Vermeulen. Wageningen UR Greenhouse Horticulture, Bleiswijk, Report No. 185.

Cultivation schedule

In the Mediterranean region, the growing period is often limited to 7–10 months of the year due to the high temperature and low air humidity which prevail during late spring and summer (Baille, 2001). High greenhouse temperatures, typically occurring from May to August, make year-round cultivation almost impossible. Production is generally seasonal with two peaks: one in spring to early summer and a second in autumn (to the end of December, if the climate is suitable) (Pardossi *et al.*, 2004). The current trend is to lengthen the crop cycle, despite some undesirable consequences on plant performance, quality and harvesting time. While there are advantages in extending the cropping season, it is also necessary to take into account that the harvest times of crops produced in the open air and in greenhouses will overlap more and the products will compete in the same market (La Malfa and Leonardi, 2001).

In Mediterranean greenhouses, two or more crops per year are already grown as either long or short cycle (Table 1). Production season and length of crop cycle depend on the species, local climatic conditions (i.e. temperature and light), availability of climate control (i.e. heating/cooling) in the greenhouse, market demand and export potential. Good planning of the production season increases the economic return for farmers, particularly if based on market analysis – for example, growers in the Jordan Valley start ‘Charentais’ melon production in November on the basis of good prospects for export to Europe.

Planting density

Plant density indicates the number of plants per unit of cultivated area and is directly linked to final yield and product quality. Plant density (plant spacing) affects light interception by the canopy and its efficiency of use by the crops. Increased plant density results in increased biomass production due to enlargement of the total crop leaf area, while single plant fresh weight and fruit size are restricted (Yang *et al.*, 2009). Optimal plant density depends on species, length of growing cycle, seasonal changes in the light, climate, and training and pruning of the crop; other considerations are greenhouse design and climate control (particularly ventilation rate). High plant density improves light interception, but if the ventilation rate



Plate 2

High plant density in high tunnels causes severe disease problems



Plate 3
Plants in front of windows prevent airflow

is low, disease problems occur (e.g. virus infections, foliar blights, leaf spots, stem, fruit and root rots) and can become severe very quickly, requiring frequent pesticide spraying (Plates 2 and 3). Excessively high density can lead to incidence of disease; plant density should be lower in long-cycle crops than in short-cycle crops. Table 2 shows the average plant density recommended for some important greenhouse vegetables.

Row orientation

Light interception is affected by both row orientation and plant density, which in turn depend on greenhouse location and the cultivation seasons. Li *et al.* (2000) reported that the normalized daily canopy irradiance with E–W orientation (compared with N–S orientation) was higher in winter at 35°N and lower in spring and summer. However, at 45° and 55°N, N–S orientation gave higher values than E–W, regardless of season.

TRAINING AND PRUNING

Training

Crops with indeterminate growth (e.g. tomato, cucumber, pepper) need to be trained in order to control the number and the position of apical meristems per plant which govern plant growth and development. In practice, controlling the number of apical meristems means controlling the number of shoot apices; this is achieved either by completely removing new shoots or by cutting off shoot tips.

Training aims to increase light penetration throughout the leaf canopy (thereby increasing light interception by photosynthetically active leaves), increase

TABLE 2
Plant density of vegetables (plant/m²) grown in different cycles

	Long cycle	Autumn	Spring	No. stems
Tomato	2.5	3–3.5	3–3.5	Single
Pepper	2–2.5		2.5–3.5	3–4 shoots
Cucumber	2.7	3.3	3.3	Single
Eggplant	1.5–2.2		2.5	2–3 shoots
Melon			2.5	Single
Zucchini	1.5		1.5	Single



Plate 4
Correct spacing gives fewer problems

**Plate 5***Plant training***Plate 6***Plastic clips and supports for trusses*

airflow, and reduce the incidence and spread of diseases. The training system adopted depends on the crop species, length of growing cycle and greenhouse design:

- Plants are supported using string (plastic or polypropylene twine).
- The string is attached to a cable stretched above the plant row (Plate 5).
- Plants are wrapped around the string or attached to it with plastic clips (Plate 6).
- In long-term, layered tomato crops, there are many different ways to attach the strings and their plants to the cables: the slip knot (by hand), metal string bobbins or a notched spool with a hook (Plate 7) (Hochmuth, 2008a).

**Plate 7***Different ways to attach the strings to the overhead cables*

Pruning

Pruning in greenhouse crops includes the complete removal of new side shoots, the removal of shoot apices and leaves, as well as fruit thinning. Most greenhouse vegetables need pruning; the pruning of shoots is essential for plant training, and there are other benefits:

**Plate 8***Layering system in soil (left) and soilless culture (right)*

**Plate 9**

Plant waste left in or around the greenhouse is a potential source of infection

- Reduction of competition between shoots within a plant for light, nutrients and water by removing unnecessary plant parts, thus increasing assimilates to each remaining shoot.
- Increase of light penetration through the leaf canopy for more efficient light interception.
- Reduction of occurrence of pests and diseases by increasing airflow among the leaves and preventing local spots of excessive humidity within the canopy.
- Improvement of fruit quality, because the reduction in the number of shoots results in more assimilates being allocated to each fruit, and the final fruit product is therefore bigger.

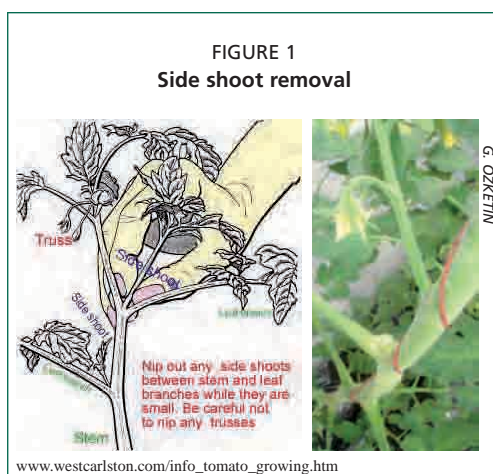
**Plate 10**

Ways to prevent pest and disease infection

Pruning may be modified to adapt to the growing season, the length of the growth cycle and the variety, but it should always be done on time and properly. Pruning is also an opportunity to inspect plants for problems with pests, diseases or nutritional disorders. In order to prevent new infection or the spread of pests and diseases, equipment should be disinfected and all waste material from pruning should be removed from the greenhouse (Plates 9 and 10).

Tomato

Plants are usually pruned to a single stem by removing all lateral (side) shoots. Late pruning of side shoots also has a negative effect on crop performance because developing side shoots compete with fruits; it also increases the risk of disease infection (Figure 1).



www.westcarlston.com/info_tomato_growing.htm

**Plate 11**

Double stem tomato plants at different growing stages

In some circumstances, two stems per plant can be allowed to develop in order to save money. In this case the apex of the main stem is pinched off at an early growth stage and two lateral shoots are allowed to develop on opposite sides of the rows. This practice is more frequent in grafted plants (which are more expensive), in order to reduce the cost of purchasing seedlings. It reduces the number of plants per unit area by 50 percent. Each stem is tied and grown like a single plant (Plate 11).

In northern Europe, with long-season tomato crops, it is quite common to allow one side shoot to grow out after the main shoot has been growing for a few weeks so that each root system supports two (or even four) shoots. This practice increases plant density and thus the number of fruits available; it is a strategy for coping with the increase in assimilates produced as the daily light integral increases and for producing fruit of one uniform size (Cockshull and Ho, 1995; Cockshull *et al.*, 2001).

The growing season and climatic conditions should be taken into consideration when deciding the number of stems per plant.

Most of the assimilates supplied to the fruit of each truss (cluster) come from the two or three leaves under that truss. If leaves are removed too early, the growth and final size of the fruit are adversely affected, but removal of the leaves under the fruit truss once fruit is at the mature green stage will speed up the ripening process, improve air circulation and reduce disease incidence (e.g. *botrytis*). It is true that old leaves, even before they start yellowing, need to be removed because they have limited access to light and thus lose more carbon through respiration than they gain carbon by photosynthesis. Their presence negatively affects crop performance. Leaf pruning is also related to layering or “leaning and lowering”.

Truss thinning is performed to obtain the fruit size required by the market (Plate 12).

**Plate 12**

Truss thinning

Pepper

The plant starts as a single stem, trained into two or more stems as soon as the first vigorous lateral stems appear. Pepper plants can be trellised according to the “Spanish” system or the “Dutch” (“V”) system:

- **Spanish trellis system.** The plant canopy is allowed to grow without pruning.

**Plate 13***Spanish trellis system***Plate 14***Pepper pruning*

The plants are vertically supported by a structure of poles and horizontal twines extended on both sides of the plant rows (Plate 13). Labour requirements are thus reduced by at least 75 percent compared with the “V” trellis system (Jovicich *et al.*, 2003 and 2004).

- **V system.** The plant generally has two or three main stems (Plate 14). All lateral shoots are removed up to the branching point and the shoots are then pruned to form a plant with several branches. The first flower (crown flower) is removed to promote vegetative growth. Only the flower on the nodes adjacent to the leaf is left on each branch (Figure 2).

**FIGURE 2
Pepper pruning**

Nederhoff, 2002

Cucumber

Fruits and lateral shoots are removed up to a height of 30 cm to encourage vigorous early vegetative growth, essential for maximum fruit production. All lateral branches are then pruned out, leaving one fruit and one leaf per node until the main stem reaches the overhead wire. After one or two leaves have developed above the wire, the growing point of the main stem can be removed (Hochmuth, 2008b) (Figure 3) and two lateral branches left. Mis-shapen or yellowish fruits should be removed as well as any old leaves below.

**FIGURE 3
Cucumber pruning**

Eggplant

Plants are pruned to have two to four main stems. Yield increases with the number of branches up to a certain threshold, which depends also on plant



Plate 15
Eggplant pruning

density. However, an excessively high stem density can negatively affect mean fruit size (and thus marketable yield and fruit quality), even though the total yield may still increase. Strong lateral branches are allowed to grow following formation of the first flower, while all lateral shoots below that height are removed. At each node, in addition to one main flower, one or more secondary flowers may develop.

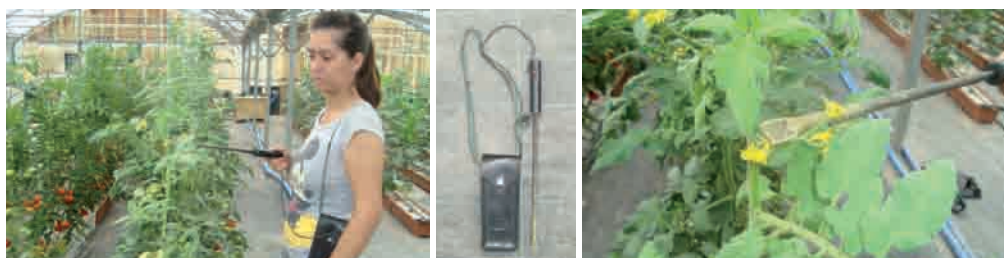
Although most secondary flowers do not set fruit, some of them may develop into a small fruit, depending on plant vigour. However, in most cases these fruits are undersized and thus non-marketable; fruit-setting on the secondary flowers is, therefore, a waste of assimilates. Despite this, the removal of secondary flowers is not usually recommended as standard pruning treatment, since the labour required exceeds the expected benefits from the small saving in assimilates. Old leaves should be removed to allow air circulation and light interception (Plate 15).

FRUIT-SETTING

The yield of most fruit-bearing greenhouse vegetables depends on the success of fruit-set which is linked to pollination; only parthenocarpic cultivars (e.g. cucumber) do not need pollination. Pollination is the transfer of pollen grains to the stigma: they are released from the anthers and usually fall onto the stigma. In greenhouses, in contrast to open field production, pollination needs assistance due to the limited air movement and high humidity. Pollination can be assisted by mechanical vibration or by bumblebees. However, pollen viability and the amount of pollen – both of which are particularly dependent on temperature – are also important for successful pollination.

Mechanical vibration

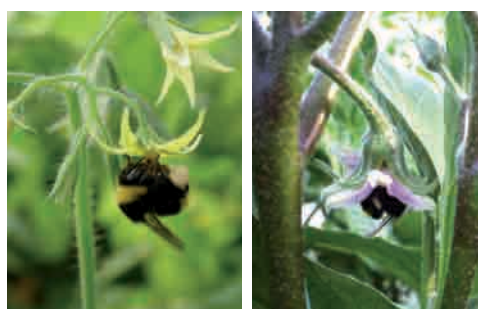
Vibrators (usually battery powered) are used on tomato by holding them against the stem of each truss for a few seconds (Plate 16). The operation should be carried out at least three times a week between 10.00 and 15.00 hours (humidity low, high pollen availability) (Hochmuth, 2008a). Mechanical vibration is a good agricultural practice, but it is time-consuming.

**Plate 16***Mechanical vibration*

Bumblebees

Bee species used as pollinators include honey bees (*Osmia cornuta*) and bumblebees (*Bombus terrestris*). Bumblebees are the most efficient and are used in greenhouses worldwide. The advantages of bumblebees in comparison to honey bees can be summarized as follows:

- Faster, visiting 8–20 flowers per minute
- More efficient, visiting 400 flowers in one trip
- Better contact because of large size
- Better worker, because of the lack of communication system

**Plate 17***Bombus terrestris*

Bumblebees are placed in the greenhouse inside the hives and remain active for about 6–8 weeks (Plate 17). The use of bumblebees for pollination has numerous advantages:

- Increased crop yield
- Higher fruit quality
- Reduction in labour costs
- Safer product
- Decrease in risk of fungal disease after use of plant growth regulators (PGR)
- Low pesticide input and use of low-toxicity pesticides – essential to avoid harming the bumblebees

Research with tomato has shown that the use of bumblebees for pollination is more effective than mechanical vibration or plant growth regulators (PGR) given the improvement in fruit number and mean fruit weight (Tables 3 and 4).

TABLE 3
Effects of treatments on fruit number (number/m²) in different cultivars of tomato

Treatment	F 144	F 198	F 248	Vivia	Mean
Bumblebees	24.61	30.17	37.45	38.95	32.79 a
Vibrator	16.60	17.30	18.40	33.80	21.53 b
PGR	16.40	22.93	16.30	22.93	19.64 b
Mean	19.20 b	23.47 ab	24.05 ab	31.89 a	24.65

Different letters indicate significant differences within the treatments based on Turkey's HSD test at P = 0.05.
Dasgan *et al.*, 2004

TABLE 4
Effects of treatments on mean fruit weight (g) in different cultivars of tomato

Treatment	F 144	F 198	F 248	Vivia	Mean
Bumblebees	155.29	134.51	144.10	144.07	144.49 a
Vibrator	112.75	101.63	108.46	86.47	102.33 b
PGR	138.95	124.16	126.05	140.88	132.51 a
Mean	135.66	120.10	126.21	123.81	126.44

PGR: plant growth regulator.
Different letters indicate significant differences within the treatments based on Turkey's HSD test at P = 0.05.
Dasgan *et al.*, 2004

TABLE 5
Number of hives for different vegetable crops

Crop	Pollination range per hive (m ²)
Tomato	2 000
Pepper	1 000
Eggplant	1 000
Melon	1 000
Courgette	1 000
Strawberry	1 000

Introduction schedule


Hives are introduced when the flowers are open. A standard hive comprises 50–60 worker bees and a queen. The approximate pollination range per hive varies according to the greenhouse vegetable crop (Table 5).

Placement of hives

Once a hive is placed in a greenhouse (Figure 4), the bumblebees need ½–1 hour to settle down before the flight hole is opened. Their activity depends on the flowering of the crop. Tiny brown spots on the stamens show when they have visited the flowers (Plate 18).

FIGURE 4
Placement of hives


Wrong



A. HANAIFI

Correct

- 0.5–1 m above the ground
- Protected against sun and condensation
- Avoidance of ants or other insects entering hives



A. HANAIFI



Plate 18
Brown marks on stamens indicate bumblebee visits

Plant growth regulators

Plant growth regulators (PGR) have been used for years in agriculture for various purposes. In greenhouse vegetable crops they can be used for parthenocarpic fruit-setting, particularly under temperature conditions that are too low or too high for standard pollination (Table 6, Plate 19). However, chemicals used as PGRs can negatively affect fruit quality (i.e. shape, size, colour, seed development), especially when doses exceed standard recommendations (Plate 20).

The most common PGRs used for fruit-set in greenhouses are β -NOA (β -naphthoxyacetic acid) and 4-CPA (4-chlorophenoxyacetic acid). Commercial use of PGRs is subject to legislative restrictions (e.g. 91/414/EEC for the European Union). Maximum residue levels (MRLs) (EC regulation 396/2005) are available at http://ec.europa.eu/sanco_pesticides/public/index.cfm.

INTERCROPPING

Intercropping is the cultivation of two or more crops together in the same area. Each crop should have sufficient space, but in order to maximize cooperation and minimize competition between crops, spatial distribution (row, strip, mixed, relay intercropping), plant density, harvesting periods and plant architecture need to be considered (Sullivan, 2003). Good management of the planting schedule, fertilization, plant protection and harvesting period is necessary to increase intercropping performance.

Intercropping performance can be assessed using the land equivalency ratio (LER), which shows the yield advantage of the intercrop over a single crop. It is the sum of the division of intercrop yields to the pure crop yields for each crop in the intercrop. It can be calculated using the equation of $LER = \sum (Y_{int}/Y_{pure})$, where Y_{int} is the yield of each crop in intercropping and Y_{pure} is the pure yield of each crop (Vandermeer, 1992; Sullivan, 2003).

TABLE 6
PGRs used for fruit-set and dosages

	β -NOA	4-CPA	4-CPA + Gibberellic acid
Tomato	1–1.5	2	
Eggplant		4	
Courgette			4 + 1



Plate 19
Dried petals which do not fall off are possible indicators of use of PGR in stem cavity



Plate 20
Fruit-sets by PGRs with undesirable effects on tomato fruit quality: fewer or no seeds, non-uniform colour, hollow fruit

- If LER is equal to 1, there is no advantage from intercropping.
- If LER is above 1, intercropping is considered advantageous.
- If LER is below 1, there is a disadvantage from intercropping.

Although intercropping has some advantages (e.g. reduced risk of total crop failure), it is not widely practised in greenhouses where the monocultural production of high-value crops is more usual. However, intercropping may be used, particularly relay intercropping, i.e. the cultivation of more than one crop simultaneously during the growing cycle. For example, leafy vegetables (e.g. lettuce, green onion) and some herbs (e.g. basil) could be intercropped with high-value vegetables (e.g. tomato) (Jett *et al.*, 2005). Intercropping can be more profitable for small-scale greenhouses because of product diversification.

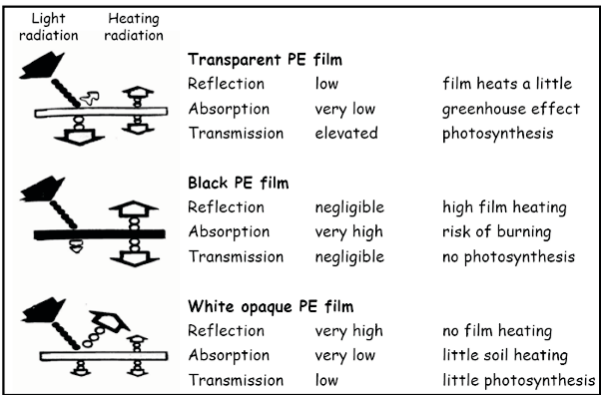
Mulching

Mulching is the covering of the soil surface with any material which separates the soil from the atmosphere. Mulching material can be either organic (e.g. crop residues such as straw) or inorganic (e.g. plastic film). It can be grown *in situ* (e.g. residues of a previous crop left on the soil surface, a cover crop grown among the rows and its residues left, or a living mulch grown as a cover crop). Alternatively, it can be grown or produced *ex situ* (e.g. straw, sawdust and plastic products). Mulching has a buffering effect which depends on the quality, quantity and durability of the material, soil type and climatic conditions (Acharya *et al.*, 2005).

To maximize the advantages of mulching, application must be appropriate to the soil, crop and climatic conditions of a site.

The most common mulch materials are plastic films (Figure 5), but their intensive use causes environmental problems as a result of their high chemical

FIGURE 5
Reflection, absorption and transmission of three mulching films



stability. Since the plastic materials used for mulching require a long time to complete their decomposition, research focuses mainly on the production of biodegradable polymers (Plate 21) which could reduce the environmental pollution resulting from the disposal of plastic films (Bilck *et al.*, 2010).



Plate 21
Biodegradable material

Advantages of mulching

- Improves soil physical properties
- Increases soil temperature (Figure 5)
- Retains soil water content
- Suppresses weeds (only opaque materials)
- Reflects light (e.g. white PE)
- Favours uniform soil wetting
- Improves soil chemical properties and biological activity (organic materials)
- Prevents fruit coming into contact with soil
- Reduces runoff losses
- Retards erosion
- Reduces salt accumulation due to capillarity rise
- Adds nutrients (e.g. organic materials)
- Prevents leaching of nutrients
- Increases efficiency of water and fertilizer use
- Provides earliness
- Increases yield
- Improves quality

Kijchavengkul, 2008

HARVESTING

Greenhouse vegetables are harvested once at commercial maturity, which depends on the species, market demand and destination (local or export). Tomato may be picked as individual fruit (sometimes without the green calyx, especially if intended for export), or the stem of the whole truss can be cut with scissors and marketed as “tomatoes on the vine” or “truss tomatoes” (“cluster tomatoes”). Fruits should be handled carefully to avoid damage, especially bruising. For each crop species there are distinct standards for classification (size, weight) and quality (well-developed or damaged), in addition to specific provisions concerning presentation and marking etc. (www.unece.org).

There are also maximum residue levels (MRL) for each product to ensure food safety. Given the increasing consumer awareness and public concern about the impact of harmful chemical residues on human health, greenhouse products should be free of chemical (e.g. pesticide) and microbiological contamination.

EU fresh fruit and vegetable requirements deal with health control (food law, hygiene, microbiological criteria, contaminants, pesticides), plant health control

(harmful organisms) and marketing standards (Froidmont, 2006). Commission Regulation 1221/2008 provides general marketing standards for all fresh fruits and vegetables and repeals specific marketing standards for 26 products. The minimum quality standards require that products be:

- intact (tolerances are permitted);
- clean (with almost no visible foreign matter);
- practically free from pests and from damage caused by pests and affecting the flesh;
- without abnormal external moisture;
- free from foreign smells or tastes;
- fit for transport and handling to arrive in good condition at the intended destination.

Minimum maturity requirements

Products must be sufficiently developed and ripe. A tolerance level of 10 percent (by number or weight) not satisfying minimum requirements is permitted in each lot; this does not cover products affected by rotting or other deterioration making them unfit for human consumption. Marketing of packages with a maximum net weight of 5 kg and containing mixes of fruit and vegetables is allowed if the products are of uniform quality and comply with the relevant marketing standard or, if no specific marketing standards exist, the general marketing standard.

GAP recommendations

- Plan the production season based on market analysis.
- Pay attention to soil management for high yield, high quality and high value:
 - Perform as little tillage as possible.
 - Maintain or restore soil organic content by manure or compost application.
 - Analyse soil and organic manure (or compost) to prevent contamination; apply adequate and balanced nutrients at appropriate times and in appropriate doses.
 - Control salinity by irrigating with small volumes, by tillage and by mulching to prevent upward movement of saline water from the deeper layers.
 - Control soil-borne pathogens by avoiding the application of chemical treatments for soil disinfection whenever possible.
- Adopt soil solarization – a non-chemical method to combat soil-borne pathogens:
 - Apply in the summer months (June, July, August).
 - Irrigate soil before and during solarization if it becomes dry.
 - Place transparent PE (25–30 µm) over the soil surface; bury the edges without gaps.
 - Leave plastic in place for 4–6 weeks.
- Use correct plant spacing:
 - Avoid too high density to prevent disease incidence.
 - Keep density lower in long-cycle crops than in short-cycle crops.
- Adopt timely and correct pruning techniques; remove all waste material to prevent new infection or the spread of pest and diseases.
- Use bumblebees for pollination:
 - Place hives 0.5–1 m above the ground.
 - Protect hives against sun and condensation of water.
 - Avoid ants or other insects entering hives.
- Adopt site-appropriate mulching for efficient management at different sites, with different soils, crops and climatic conditions.
- Handle harvested fruit carefully to avoid damage, especially bruising. For each crop, take account of distinct quality standards for the classification (size, colour), tolerances, definitions (i.e. well-developed or damaged) and classification of defects.

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15. Integrated pest management and plant hygiene under protected cultivation

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INTRODUCTION

Integrated pest management (IPM) offers a practical method for the effective management of pests under greenhouses. Through the adoption of sound cultural practices and monitoring techniques, accurate problem identification, and timely implementation and evaluation of appropriate management strategies, growers can improve vegetable production while minimizing their reliance on routine pesticide applications. IPM makes use of many different management options: cultural, physical, mechanical, biological and chemical. Routine crop inspection alerts growers to developing pest and cultural problems while they are still minor and easily manageable. Early detection and intervention is the foundation of an IPM programme.

Greenhouse management for the control of insects and diseases depends on: the local climate; external disease and insect pressure; the greenhouse structural design; availability of climate control equipment; and the skill level of the greenhouse workers.

INSECT PEST EXCLUSION TECHNIQUES

Sanitation

It is important to keep the area around the exterior and interior of the greenhouse free from weeds and other plants that could harbour pests. An inventory should be made of plants in the area around the greenhouse to determine their relative risk as a pest harbour: remove high risk plants, with the exception of those that could attract natural enemies and pollinators.

Airlock entrance

Walk-in doorways provide an easy entrance for many pests; growers need to evaluate strategies to reduce the likelihood of pest entrance. In greenhouses with fan and pad ventilation, an airlock entrance room is essential: attached to the

exterior of the greenhouse and enclosing the entry doorway, its double-door system allows workers to enter the airlock room and close the outside door behind them before entering the greenhouse production area. Without the airlock room, the fans pull air in through the unprotected doorway rather than through the screened opening at the opposite end of the greenhouse, and it is common to see pest infestations beginning in plants close to an unprotected doorway. Even in passively ventilated greenhouses, a secure entrance room is important to regulate the easy entrance of pests to the production area. Such rooms can also be used as a footbath and hand-washing area, and for any other sanitation practices for workers.

Insect screening

Screens with a fine mesh to keep insects out of the greenhouse can be an important element in an IPM programme and may be used effectively in both passively ventilated and fan and pad greenhouses. Any screens added to a ventilation opening will reduce airflow through that opening. It is therefore important to follow the manufacturer's recommendations to increase the surface area covered by the screen to compensate for the reduction in airflow, which in turn can burn fan motors or reduce cooling by reducing ventilation.

Reflective or metallized mulches

Highly reflective or metallized plastic mulches have been used in agriculture for many purposes and are particularly effective in reducing the entry of whitefly and thrips. Combining screening and metallized mulch results in the greatest total reduction of whitefly entry.

Scouting and insect monitoring

Even with implementation of all the above exclusion techniques, some insects will still enter the greenhouse. Early detection of pests in the crop is crucial and pest monitoring tools and techniques must be used, for example, yellow sticky traps, plant scouting and examination of plants with a hand lens. Pest infestations are usually location-specific; for example, hot spots of pests near ventilation or doorway openings are common.

Control strategies

If pest populations build to a threshold level requiring control measures, growers must be prepared for the immediate implementation of a control plan taking account of the current specific spray or biological control recommendations:

- Choose either an IPM or traditional pesticide strategy. Many excellent biological control agents are now available against common pests; however, in the case of virus transmission from insect vectors (whitefly transmitting yellow leaf curl virus), be cautious with biological control strategies because a low level of a pest population is necessary to “feed” the beneficial agent.

- Carefully examine pesticide choices and use the safest effective materials available.
- Follow a good pesticide rotation programme to slow the development of pesticide resistance. Many “soft” or “biorational” pesticides (e.g. soaps, oils, neem products and *Bacillus thuringiensis* [Bt]) can play an important role in an IPM programme for greenhouse vegetables.

SOIL PREPARATION

Soil should be slightly acid (around pH 6.5). If in doubt, soil analysis is required through the local extension office, by a private lab, or with a commercial soil test kit. Lime can be used to increase soil pH, and sulphur to lower pH.

Adequate levels of soil fertility need maintaining through addition of potassium- and phosphorus-releasing materials, such as commercial fertilizers or animal manures. Soil testing should be done every three years to determine the levels of these important nutrients. The regular addition of organic matter, such as yard waste, compost and manure, is important for a biologically active, healthy soil.

PLANT SELECTION

- Select vegetable varieties with maximum insect and disease resistance.
- Buy plants from a reputable nursery which can guarantee that they are free from disease and insects with a phytosanitary control certificate; alternatively, grow your own from seed of which the health status has been checked.
- Space plants properly and thin young vegetables to a proper stand. Overcrowding causes weak growth and reduces air movement, resulting in increased insect and disease problems.
- Keep down weeds and grass. They often harbour pests and compete for nutrients and water. Leaf and other organic mulches are extremely effective for weed control, as are inorganic weed mats, plastic and other fabrics.
- Avoid injury to plants – broken limbs, cuts, bruises, cracks and insect damage are often the site for infection by disease-causing organisms.
- Remove and dispose of infected leaves from diseased plants as soon as they are observed; likewise, remove severely diseased plants before they contaminate others. The infected plants and leaves can be used to make compost.
- Clean up crop refuse at the end of each day’s work.

DISEASE MANAGEMENT

Vegetable diseases include early blight, late blight, powdery mildew, downy mildew, damping-off, and viral and bacterial diseases. For effective control, they must be properly identified. An integrated approach to disease management involves the use of resistant cultivars, sanitation, sound cultural practices and the proper use of the correct pesticides.

RESISTANT CULTIVARS

The number of pest-resistant cultivars in various greenhouse crops has greatly increased in recent years. In some cases, using a resistant cultivar is the most successful method in an IPM strategy. One of the challenges in greenhouse vegetable crop production is the need for multiple resistance and growers should carefully research information on new resistant cultivars with the potential to fit production and market demands. A cultivar must not only solve a specific pest problem, but must also be acceptable to consumers. It is advisable to evaluate new cultivars in a small portion of the crop area before switching entirely to an untested cultivar.

GROWING MEDIA

Soilless media are generally purchased in bags or custom mixed on site and contain no field soil. Preventive applications of one or several fungicides or biological fungicides may be necessary with some crops that are prone to damping-off.

Field soil, whether used by itself or as an amendment in a soilless medium, must be treated to eliminate soil-borne plant pathogens, insects and weed seeds. Once the soil has been treated, care must be taken to avoid reinfestation.

TECHNIQUES TO REDUCE HIGH HUMIDITY

High relative humidity is one of the major contributing factors to *Botrytis* blight (a common fungal disease of plants under greenhouses) and other serious diseases. Warm air has the capacity to hold more moisture than cool air; therefore, on warm days, greenhouse air is more humid. As the air cools in the evening, the moisture-holding capacity drops until the dew point is reached; water then begins to condense on surfaces. One recommended practice is to heat and vent two or three times per hour in the evening after the sun goes down and early in the morning at sunrise.

Horizontal airflow (HAF) can also reduce condensation. HAF fans keep the air moving in the greenhouse, helping to minimize temperature differentials and cold spots where condensation occurs. Air that is moving is continually mixed; the mixed air along the surface does not cool below the dew point so does not condense on plant surfaces.

Humidity within the plant canopy can also be reduced by adopting appropriate cultural practices, including proper watering practices and spacing of plants. However, since most vegetable plants are grown in flats that are spaced flat to flat, reducing humidity in the canopy is not easy. Proper planting dates, plant nutrition, watering practices and height management are all effective techniques to help prevent lush, overgrown plants, thereby reducing humidity within the canopy.

FUNGICIDES

Fungicides are potentially very effective with some diseases, but may be ineffective with others (Table 1):

- Root diseases: apply broad-spectrum fungicides as a drench on a preventive basis, read directions on the pesticide labels, and note that an additional application of water may be necessary.
- Foliage diseases: obtain thorough spray coverage, and treat when disease is first evident.

BIOFUNGICIDES

Biofungicides are biological fungicides that contain living organisms (fungi or bacteria) which attack plant pathogens and thus help to fight the diseases they cause. They can be used as part of an integrated disease management programme to reduce the risk of pathogens developing resistance to traditional fungicides. Currently, there are no pathogens resistant to biological fungicides. Furthermore, they have a lower re-entry interval (REI) than traditional fungicides and many can be used in rotation with other chemicals.

Biological fungicides can suppress diseases in a variety of ways:

- Compete directly with the pathogen.
- Shield the roots by growing a defensive barrier around them.
- Produce an antibiotic or another toxin that kills the target organism.
- Attack and feed upon the pathogen (in this case, the biological fungicide must already be present when the pathogen appears or before).
- Induce the plant to turn on its own defence mechanisms.

Biofungicides provide preventive treatment and should be used as part of a regular monitoring programme where root health and crop quality is evaluated. They do not cure diseased plants and must be applied before the onset of the disease, used in conjunction with standard cultural practices for disease prevention. Storage conditions, soil and air temperatures, and the use of other chemicals all affect their efficacy. Most biological fungicides have a limited shelf-life of one year. A number of products are commercially available for use on vegetables (Table 1).

SPECIFIC DISEASES

Late blight (*Phytophthora infestans*)

Late blight disease has worldwide distribution; it attacks tomato and causes extensive damage, especially in the temperate zone. It is a polycyclic disease, i.e. many cycles of infection are possible in one growing season. Disease increases when relative humidity is 90–100 percent. It occurs in a wide range of temperatures from 3 to 26 °C, but the optimum temperature range is 18–22 °C.

TABLE 1

Selected fungicides and bactericides labelled for vegetable plants

Fungicide	Targeted pest	Labelled crops	Comments
Basic copper sulphate (Cuprox Ultra 40 D Disperss), 12 hr REI, Group M1	Many diseases incl. angular leaf spot, downy mildew, Alternaria blight, anthracnose, bacterial blight, bacterial spot (depending on crop)	Many incl. cucumbers, eggplant, peppers, tomatoes	Crops grown in greenhouse may be more sensitive to copper injury so the user should determine plant sensitivity. Observe for 7–10 days for symptoms of injury.
<i>Bacillus pumilus</i> (Sonata), 4 hr REI, Group 44, OMRI listed	Downy mildew, powdery mildew	Many incl. cole crops, cucurbits, fruiting, leafy vegetables	Begin applications when greenhouse conditions favour disease development.
<i>Bacillus subtilis</i> (Serenade), 4 hr REI, Group 44, OMRI listed	Many diseases incl. downy mildew, powdery mildew, bacterial spot, early blight	Many vegetables incl. broccoli, leafy vegetables, cucurbits, peppers, tomatoes	Preventive biofungicide. Thorough coverage essential.
<i>Bacillus subtilis</i> (Cease), 4 hr REI, Group 44, OMRI listed	Many diseases incl. leaf spots, powdery mildew, botrytis blight, downy mildew	Many incl. cole crops, cucurbits, fruiting vegetables, leafy vegetables,	Begin applications when greenhouse conditions favour disease development. Thorough coverage essential.
Copper Hydroxide (Champ DP Dry Prill, Champ Formula 2 Flowable, Champion WP, Champ WG [OMRI listed], Kocide 101, Kocide 2000, Kocide 4.5LF, Kocide DF), 24 hr REI, Group M1	Leaf spots, <i>Anthracnose</i> , bacterial spots and other diseases (see label)	See labels for specific crops	See labels for specific usage instructions.
Copper salts of fatty and rosin acids (Camelot), 12 hr REI, Group M1	Many incl. bacterial leaf spots, leaf spots and blights, downy mildew, powdery mildew	Greenhouse vegetables (see label for specific crops)	See label for specific usage instructions.
Cuprous oxide (Nordox 75 WG), 24 hr REI, Group M1	<i>Anthracnose</i> , <i>Phomopsis</i> , <i>Botrytis</i> , various leaf spots and blights (see label)	Tomatoes, peppers, eggplant	Begin applications when disease first threatens.
Dichloran (Botran 75-W), 12 hr REI, Group 14	<i>Botrytis</i> , white mould (<i>Sclerotinia</i>)	Cucumbers, leaf lettuce, tomatoes	Seedlings or newly set transplants of tomatoes may be injured by drenching.
Fenhexamid (Decree 50WDG), 12 hr REI, Group 17	<i>Botrytis</i>	Fruiting vegetables, tomatoes, cucumber, leafy greens (except spinach)	Thorough coverage needed. Do not make more than two consecutive applications. Do not apply in the field.
Horticultural oil, paraffinic oil (Ultra-Pure Oil), 4 hr REI, NC Saf-T-Side, spray oil emulsion fungicide, insecticide and miticide), 12 hr REI, NC, OMRI listed (Organic JMS Stylet Oil)	Powdery mildew	Cucurbits, melons, squash and others	Contact fungicide. Application should be made when disease is first noticed. See label for information on plant safety. Use lower label rates in the greenhouse. Applications should be preceded by a phytotoxicity check to ensure that material is safe.
Hydrogen dioxide (Oxidate), 0 hr REI (non-spray), 1 hr REI (spray), OMRI listed	Many incl. mildews, leaf spots and blights, and root	Tomatoes, peppers, leafy and cole crops, cucurbits and others	Strong oxidizing agent. Contact, oxidizing sanitizer.
Insecticidal soap, potassium salts of fatty acids (M-Pede), 12 hr REI, OMRI listed	Powdery mildew	Greenhouse cucumber	Works by contact. See label for usage instructions.
Kaolin (Surround WP), 4 hr REI, Group NC, OMRI listed	Powdery mildew	Cucurbit vegetables	Forms a mineral-based particle film resulting in a dry, white film. May be unsightly for retail sales. Uniform coverage important for effectiveness.

TABLE 1 (cont'd)

Selected fungicides and bactericides labelled for vegetable plants

Fungicide	Targeted pest	Labelled crops	Comments
Mancozeb (Dithane F45, DF), 24 hr REI, Group M3	Leaf spot diseases, seed treatment for damping-off, seed rots and seedling blights, and downy mildew	Tomatoes, cucumbers, melons, summer squash and others	Broad-spectrum protectant fungicide.
Maneb (Maneb 75 DF, Maneb 80WP, Manex), 24 hr REI, Group M3	Anthraco-nose, leaf spots, early blight, late blight	Tomatoes (greenhouse)	Protectant fungicide.
PCNB (Terraclor 75 WP, Terraclor 15G, Terraclor 400 Flowable, Turfcide 10% Granular), 12 hr REI, Group 14	Root and stem rot, damping-off (<i>Rhizoctonia solani</i>)	Vegetable bedding plants: limited to container-grown broccoli, Brussels sprouts, cabbage, cauliflower, peppers, tomatoes	Protectant fungicide. 400 Flowable and 75WP: Apply as a soil drench. 15G and Turfcide: Used as growing media mix. See label for additional information.
Potassium bicarbonate (EcoMate Armicarb "O") (Kaligreen) 4 hr REI, (Milstop) 1 hr REI, Group NC, OMRI listed	Powdery mildew and others	Many vegetables incl. cabbage, cucumber, eggplant, broccoli, cauliflower, lettuce, peppers, tomatoes, squash	Contact fungicide. Thorough coverage essential. Potassium bicarbonate disrupts the potassium ion balance in the fungus cell, causing the cell walls to collapse.
Propamocarb HCl (Previcur Flex), 12 hr REI, Group U	<i>Pythium</i> , <i>Phytophthora</i>	Tomatoes, cucurbits, peppers, leaf lettuce	For prevention of root rot and damping-off. Phytotoxicity may occur if applied directly to dry growing media, especially in intense sunlight.
Pyrimethanil (Scala SC), 12 hr REI, Group 9	Grey mould (<i>Botrytis</i>), early blight (<i>Alternaria</i>)	Tomatoes	Apply only in well ventilated greenhouses and ventilate for at least 2 hours after application. Phytotoxicity may occur in unventilated greenhouses with relative humidity above 80%.
<i>Streptomyces griseoviridis</i> (Mycostop, Mycostop Mix), 4 hr REI, Group NC, OMRI listed	<i>Fusarium</i> , <i>Alternaria</i> , suppression of <i>Botrytis</i> , and root rots of <i>Pythium</i> , <i>Phytophthora</i> and <i>Rhizoctonia</i> in the greenhouse	Many incl. lettuce, cole crops, cucumbers, melons, peppers, tomatoes	Preventive biofungicide. Contains a beneficial bacterium. Repeat applications may be needed. Use as a soil spray or drench.
<i>Streptomyces lydicus</i> (Actinovate SP), 1 hr REI, Group NC, OMRI listed	Suppression of downy mildew, powdery mildew, <i>Botrytis</i> , <i>Pythium</i> , <i>Phytophthora</i> , and <i>Rhizoctonia</i>	All greenhouse vegetables	Preventive biofungicide that suppresses diseases.
<i>Streptomyces lydicus</i> (Actino-Iron), 4 hr REI, Group NC, OMRI listed	Suppression of <i>Fusarium</i> , <i>Pythium</i> , <i>Rhizoctonia</i> , <i>Phytophthora</i> and others	Greenhouse vegetables	Preventive biofungicide that suppresses diseases. Also, contains iron and humic acid.
<i>Streptomyces sulphate</i> (Agri-mycin 17), 12 hr REI, Group 25	Bacterial spot	Tomatoes, peppers	Repeated applications can result in resistant bacteria. Do not apply through any irrigation system.
Sulphur (Microthiol Disperss) (Micro Sulph), 24 hr REI, Group M2	Powdery mildew	Microthiol Disperss: crucifers, cucurbits, peppers, tomatoes Micro Sulph: many incl. cole crops, cucumbers, eggplants, greens, peppers, tomatoes	Crops grown in greenhouses may be more sensitive to sulphur injury, so the lowest label right should be tried initially. Do not use within 2 weeks of an oil spray treatment.
<i>Trichoderma harzianum</i> (PlantShield HC) (RootShield Granules) (RootShield WP), 0 hr REI, Group NC, OMRI listed	<i>Pythium</i> , <i>Rhizoctonia</i> , <i>Fusarium</i> , <i>Cylindrocladium</i> and <i>Thielaviopsis</i>	Fruiting vegetables, leafy vegetables, cole crops	Preventive biofungicide. It will not cure diseased plants. Avoid applications of fungicides at least one week before or after application (foliar applications only for non-food crops.)

Symptoms

Random brown spots appear in the plants above ground level. The spots are water-soaked and may rapidly grow into pale green to brown lesions, covering a wide area, including stems, leaves and fruits. The small infected fruit are dark brown and appear burnt as if damaged by fire; early in the morning a very soft white mould appears on the fruit surface. This disease spreads rapidly and in a few days can completely destroy a crop, especially in greenhouse-grown tomato. Late blight only affects pepper plants at the cotyledon stage as plants emerge from the soil medium in the greenhouses.

Management

- Control weeds.
- Remove plant debris between crop cycles and during production.
- Dispose of diseased plants and debris in plastic bags; keep bags closed to prevent the spread of spores to uninfected plants during removal from the greenhouse.
- Reduce humidity and leaf wetness duration to prevent spore germination, provide good air circulation and reduce humidity within the canopy.
- Pay attention to proper planting dates, soil fertility, watering and vegetative development to prevent plants from becoming overgrown, with the aim of reducing humidity within the canopy.

Early blight (*Alternaria solani*)

Early blight disease of tomato and other solanaceous crops has worldwide distribution and is a major concern to growers. It is polycyclic, and when transplants are affected (known as “collar rot” in seedlings), losses can reach 40 percent. Favourable environmental conditions for early blight occurrence are warmth and humidity. Spores germinate and infect plants in a broad range of temperatures (5–40 °C), but the optimal range is 20–28 °C. Increased leaf maturity, heavy fruit load, crowded plants, heavy rainfall, dew and shading all enhance disease development.

Symptoms

Symptoms appear on leaves and stems, initially on the older leaves as small, dark necrotic spots that develop into lesions. The spots and lesions then spread upwards in the plant foliage as the disease progresses; young leaves are relatively resistant. The lesions have the distinctive shape of a target board with concentric rings. As the necrotic lesions expand on the leaves, the leaves become blighted and subsequently defoliated.

Management

There are no commercial tomato cultivars with a sufficient level of resistance to early blight and appropriate cultural practices must be adopted to manage the disease:

- Crop rotation, sanitation and maintenance of host vigour.
- Reduction of humidity and leaf wetness duration to prevent spore germination, provide good air circulation and reduce humidity within the canopy.
- Attention to proper planting dates, fertility, watering and height management to prevent plants from becoming overgrown, with the aim of reducing humidity within the canopy.

Botrytis blight (*Botrytis cinerea*)

Botrytis can cause leaf blight, cankers, damping-off and root rot. Plants may be attacked at any stage, but new tender growth, freshly injured tissues and dead tissues are most susceptible.

Symptoms

Botrytis blight produces characteristic grey fuzzy spores on the surface of infected tissues. Air currents and splashing water can easily disseminate the spores. In general, germination of spores and infection are dependent on a film of moisture lasting 8–12 hours, relative humidity of at least 90 percent and temperatures between 13 and 18 °C. After infection, colonization of plant tissues can occur at temperatures of up to 21 °C.

Management

Management of environmental conditions, such as temperature, humidity and duration of leaf wetness, together with sound cultural practices and use of fungicides, will help prevent disease development:

- Control weeds.
- Remove plant debris between crop cycles and during production.
- Dispose of diseased plants and debris in plastic bags; keep bags closed to prevent the spread of spores to uninfected plants as the bag is removed from the greenhouse.
- Reduce humidity and leaf wetness duration to prevent spore germination, provide good air circulation and reduce humidity within the canopy.
- Pay attention to proper planting dates, fertility, watering and height management to prevent plants from becoming overgrown, with the aim of reducing humidity within the canopy.

Powdery mildew (*Leveillula taurica*)

Powdery mildew may occasionally occur in vegetable transplants, including tomato, eggplant and other solanaceous crops, as well as cucurbit crops. Powdery mildew, unlike many foliar diseases, does not need free moisture on the leaf to thrive. Favourable environmental conditions include high relative humidity (> 95%), moderate temperatures of between 20 and 30 °C and relatively low light levels. Infections may be more common in spring when day and night temperature difference encourages high relative humidity levels, especially at night.

Air currents and water splashing in the greenhouse easily move these spores. Once a spore lands on a plant, it may take as little as 3 days (but more often 5–7 days) for infection to develop.

Symptoms

Powdery mildew is easily recognized by its white talcum-like growth. Faint, white mycelium may develop on leaves and stems, with yellow margins. When symptoms develop on the more mature leaves, powdery mildew is harder to detect and seems to occur “overnight”, catching many growers unaware. As soon as environmental conditions are favourable, powdery mildew develops into an epidemic as more leaves become infected.

Management

- Maintain proper plant spacing to reduce relative humidity levels within the plant canopy and improve spray coverage.
- Keep relative humidity levels below 90 percent in the greenhouse. Heat and ventilate in the late afternoon and early morning to reduce high relative humidity at night.
- Clean the greenhouse thoroughly between crops, removing all weeds that could be potential hosts.

Downy mildew (*Pseudoperonospora cubensis*)

This disease is the most important foliar disease of cucurbits: infected plants produce very little marketable fruit and may die; loss of leaves also exposes the fruit to sunscald. Disease development requires 6 hours of 100 percent relative humidity at the leaf surface in a broad range of temperatures from 5 to 30 °C (optimal range 15–20 °C).

Symptoms

Symptoms occur only on leaves; they begin as small, yellow spots, often angular, on the upper surface of the leaves. On the underside of the leaf, these spots appear as a grey-black mildew. Lesions appear first on older leaves and spread to newer growth, followed by general yellowing. Eventually, progressively larger areas die and turn light brown.

Management

Disease development may be prevented by:

- management of environmental conditions (e.g. temperature, humidity and duration of leaf wetness);
- adoption of sound cultural practices; and
- use of fungicides.

Damping-off of seedlings (*Rhizoctonia* sp., *Fusarium* sp., *Phytophthora* sp., *Pythium* sp.)

Damping-off is a common disease in germinating seeds and young seedlings. Several fungi are capable of causing damping-off, including *Rhizoctonia*, *Alternaria*, *Sclerotinia* and the water moulds, *Phytophthora* and *Pythium*. Soil-borne fungi do not usually produce air-borne spores, but are easily transported from contaminated soil to pathogen-free soil by infected tools, hose ends, water splash and hands. Young seedlings are most susceptible to damping-off; however, later in the crop cycle, the same pathogens may cause root and stem rot.

Symptoms

Symptoms include seedlings failing to emerge or wilting, often with a stem lesion that appears water-soaked or dark, necrotic and sunken at the soil line. The disease usually spreads radially from a central point of origin; therefore, plants often die in a circular pattern. Vegetable seeds germinated in poorly drained, cool soils are especially susceptible, and young plants that do emerge are weak and often wilt at or below the soil line. Tomato and pepper seedlings may be girdled by brown or black sunken cankers; stems of these plants may shrivel and become dark and woody. While plants do not necessarily collapse, they remain stunted and die after transplanting.

Management

Prevention is the only effective approach, because damping-off is difficult to stop once symptoms occur. There are several strategies to prevent damping-off:

- Use only certified disease-free seed from reputable seed companies.
- Use fungicide-treated seed: certain fungicides are labelled for damping-off for selected vegetable crops.
- Use pasteurized soil, compost-based or soilless mixes.
- Avoid overwatering, excessive fertilizer, overcrowding, poor air circulation, careless handling and planting too deeply.
- Provide adequate light for rapid growth.

White mould (*Sclerotinia sclerotiorum*)

Most common in the greenhouse during winter and spring, white mould infects leaves, stems and fruits. The infected spot of mould resembles white cotton and covers the infected parts of the plants, including stems, leaves and fruits. Inside the discoloured stems, the fungus produces hard, black sclerotia.

Management

- Practise strict sanitation, removing debris from the greenhouse to prevent renewed infection.
- Control the quantities and the duration of irrigation to reduce soil wetness.
- Adopt sound cultural practices and fungicides to help prevent disease development.

BACTERIAL DISEASES

Bacterial leaf spot (*Xanthomonas campestris* pv. *vesicatoria*)

Bacterial leaf spot is caused by *Xanthomonas campestris* pv. *vesicatoria* and survives on spontaneous tomato, plant debris, soil and seeds. It is spread by heavy rainfall, wind and seeds. Disease development is favoured by warm temperatures (24–30 °C) and high relative humidity.

The symptoms are water-soaked circular brown spots during rainy periods. On green fruits, lesions become slightly raised and surrounded by greenish white halos that eventually turn irregular and brown, with a sunken scabby surface. While it occurs primarily on peppers, all above-ground parts of tomatoes are also susceptible. The spots on the leaves are chocolate brown and irregularly shaped with areas of dead leaf tissue; initially they are less than 0.6 cm in diameter. Severely spotted leaves appear scorched and defoliation may occur. It is most prevalent during moderately high temperatures and long periods of leaf wetness.

Bacterial speck (*Pseudomonas syringae* pv. *tomato*)

Bacterial speck, *Pseudomonas syringae* pv. *tomato*, occurs on tomato but not on pepper. The bacterium is seed-borne and can survive in crop residue for up to 30 weeks. It spreads with heavy rainfall, by mechanical means and through seeds, especially under conditions of high humidity and low temperature (18–24 °C).

The symptoms are numerous small dark brown to black lesions with a yellow margin on the leaves. On the fruits, minute lesions develop that are dark and over 1 mm in diameter. Bacterial speck is usually distinguished from bacterial spot by the size of the lesions; however, the symptoms are sometimes similar.

Bacterial canker (*Clavibacter michiganensis*)

Bacterial canker in tomato is caused by *Clavibacter michiganensis*. The bacterium is seed-borne but can survive on plant debris in the soil for one year; it can also

survive in the greenhouse on wooden stakes and flats. Wilt, leaf scorch, canker, pith necrosis and fruit spot may occur singly or in combination, depending on the circumstances. When the bacterium is carried in the seed, the vascular system becomes colonized, resulting in wilt, pith necrosis and external cankers. Wilt initially occurs on one side of a leaf or one half of a plant because only a portion of the vascular system is blocked. Cankers and pith necrosis occur in later stages of disease development. Cankers are dark and water-soaked in appearance and often exude bacteria that are easily spread to adjacent plants. When leaf scorch occurs, the petioles usually bend downwards, while the leaf edges curl up. The margins of the leaves become brown with a yellow border on the inside. Scorching of the foliage often develops in the absence of wilt or stem canker. Transplants may not express symptoms until 6–8 weeks after infection and initial symptom expression is accelerated by environmental stress.

Bacterial wilt (*Ralstonia solanacearum*)

Bacterial wilt caused by *Ralstonia solanacearum* can survive in weeds and seeds, and in soil for 2–10 years. It is disseminated by running water, soil movement or movement of infected transplants. Disease development is favoured by high temperatures (30–35 °C) and high relative humidity. The symptoms are dark brown vascular systems in the stem of infected plants; the pith and cortex become dark brown and the infected plant wilts completely.

Bacterial soft rot (*Erwinia carotovora* sp. *carotovora*)

The bacterium *Erwinia carotovora* sp. *carotovora* survives in soil, plant debris and weeds. It is spread by surface irrigation of soil, by wind and seeds, and through cultural practices. Disease development is favoured by warm temperatures (25–30 °C) and high relative humidity.

The disease causes the plant to wilt rapidly; the pith usually disintegrates, becoming wet and slimy and leaving a hollow stem. Whole fruit may become a soft, watery, colourless, decayed mass in 3–5 days. Infected plant parts produce a foul odour that is very characteristic.

Angular leaf spot (*Pseudomonas syringae* pv. *lachrymans*)

Angular leaf spot on cucumber is caused by *Pseudomonas syringae* pv. *lachrymans*. It is seed-borne and survives beneath the seed-coat, and upon germination the cotyledons become infected. It can also survive in crop residues for 10 months, and in the soil for about 140 days at 5–15 °C. It is spread by rainfall and insects, and through cultural practices. Disease development is favoured by warm temperatures (24–27 °C) and high relative humidity.

Symptoms are water-soaked spots on the leaves, becoming yellow necrotic spots confined by veins giving them an angular appearance. The necrotic centre may drop out.

Management of bacterial diseases

Bacteria can be introduced via infected seeds, infected transplants purchased from another operation, or directly in the field via crop residues; they can also survive on weeds in the same family as the host crop. A similar management approach can be adopted for all the above bacterial diseases.

Bacterial disease management – GAP recommendations

- Use certified seed from a reputable source.
- If you do not grow your own transplants, ensure that the transplant grower follows a disease management programme (to start a bacterial disease management programme at transplanting time is far too late).
- Promptly remove infected plants and adjacent plants to prevent further infection.
- Avoid unnecessary handling of plant material.
- Reduce extended leaf wetness: never allow dew to form on the plants; minimize the length of time the leaves are wet; carry out irrigation early in the day, under conditions in which the foliage can dry in 1–2 hours; maintain good ventilation (one of the most important management factors in controlling bacterial diseases in the greenhouse).
- Monitor the plants in the greenhouse: at the first sign of bacterial disease symptoms, remove the affected plants and as many surrounding trays as possible (plants in surrounding trays may be infected and could spread the pathogen even when not yet showing symptoms).
- Disinfect all benches, equipment, flats and stakes.
- Include copper in the disease management programme: there are no products available to cure bacterial diseases, but copper fungicides can slow bacterial disease development, and if used correctly (preventively) they can avert an outbreak, even if the pathogen is present, by keeping bacterial populations low. A number of copper products are registered for bacterial disease control.

VIRAL DISEASES

Viral diseases may infect hundreds of plant species including tomatoes, peppers, eggplant and cucumber. Most viruses are spread by insect vectors, such as whitefly, aphid and thrips; others are seed-borne and mechanically transmitted (Table 2).

Tobacco mosaic virus (TMV)

Typical mosaic marks appear on the foliage and yield is significantly reduced. The most common symptoms are light and dark green mottling and dark brown discoloration on tomatoes, making them unfit for consumption.

Cucumber mosaic virus (CMV)

- **Tomato.** The leaves are affected more than the fruit; plants are often stunted, have short internodes, and may have extremely distorted and malformed leaves, known as fern leaf.

- **Cucumber.** Fruit and leaves are both affected, as the leaves become mottled, distorted and wrinkled, and their edges begin to curl downwards; the internal part of the fruit turns brown, making it unfit for consumption or processing.
- **Pepper.** Severe mosaic forms on the foliage; older leaves may have large necrotic rings, fruit may be malformed, and conspicuous yellow concentric rings or spots often appear on the fruit from infected plants.

Potato virus Y (PVY)

The most useful symptom for diagnosis is a mosaic pattern developing along the veins, commonly referred to as vein-banding. With early infection, plants are stunted, fruit-set is reduced and fruits are covered in distinct mosaic patterns making them unmarketable.

Tomato yellow leaf curl virus (TYLCV)

Infected tomato plants initially show stunted and erect or upright plant growth; plants infected at an early stage of growth will show severe stunting. The critical symptom for diagnosis is when the leaves become small and curl upwards; they show strong crumpling and interveinal and marginal yellowing. The internodes of infected plants become shortened and growth is stunted, resulting in plants having a bushy appearance. Flowers formed on infected plants commonly do not develop and fall off (abscise). Fruit production is dramatically reduced, particularly when plants are infected at an early age.

Tomato spotted wilt virus (TSWV)

- **Tomato.** The symptoms appearing on leaves, petioles, stems and fruit vary, depending on the stage at which plants become infected. Young leaves may show small, dark brown spots and eventually die. Dark brown streaks appear on stems and leaf petioles. Growing tips are usually severely affected with systemic necrosis and greatly stunted growth. The plant may exhibit one-sided growth. Tomato fruit-set on severely infected plants displays very characteristic symptoms: immature fruits have mottled, light green rings with raised centres; the unique orange and red discoloration patterns on mature fruits make them unmarketable.
- **Pepper.** The virus may cause sudden yellowing and browning of young leaves which later become necrotic. Long necrotic streaks appear on stems extending to the growing tips. Fruits formed after infection display large necrotic streaks and spots, while younger fruit may be completely necrotic.

Cucumber green mottle mosaic virus (CGMMV)

In the early stage of infection, pale yellow spots develop on the leaves at the top of the plant. Stunting is common in the infected plants. In the late stage of infection, leaf mosaic and fruit mottling can be seen.

TABLE 2
Main viral diseases of vegetable crops by host and means of transmission

Transmission	Crop		
	Tomato	Pepper	Cucumber
Seed-borne	TMV	TMV	CGMMV
Mechanical	TMV	TMV	CGMMV
Aphids	CMV, PVY	CMV, PVY	CMV, ZYMV
Whiteflies	TYLCV	-	CVYV, CYCDV
Thrips	TSWV	TSWV	

Zucchini yellow mosaic virus (ZYMV)

Symptoms are a yellow mosaic, severe leaf and fruit distortion, necrosis and severe plant stunting.

Cucumber vein yellowing virus (CVYV)

The virus causes pronounced vein clearing, chlorosis and finally general necrosis. A light to dark green mosaic appears on the fruit.

Cucurbit yellow stunting disorder virus (CYSDV)

Interveinal chlorotic spots appear on mature leaves. The yellow spots enlarge and may eventually coalesce, resulting in the yellowing of the entire leaf except for the veins which remain green. The leaves may roll up and turn brittle.

Management of virus diseases

Most viruses infecting vegetables are transmitted by sap-sucking insects. Weeds and other hosts are crucial in the life cycle of many viruses and their vectors. Infected plants cannot be cured: control involves the prevention or delay of infection. No single method is likely to provide perfect control, but if a combination of the management options are utilized, it can be possible to successfully implement disease control.

Virus disease management – GAP recommendations

Exclusion/avoidance:

- Plant virus-free seeds and seedling transplants.
- Grow crops in areas where the disease seldom occurs or during periods when the virus or its vector are at a low level.

Reduction in virus inoculums level:

- Control weeds and other virus hosts and insect vectors.
- Destroy old crops promptly.
- Separate new crops from maturing crops and avoid overlapping crops, especially continuous year-round cropping.

Protection of the host:

- Plant virus-resistant or virus-tolerant varieties.
- Use highly reflective mulches and oil sprays to deter insects.
- Use barrier crops and bare land to reduce vector activity.
- Use insecticides strategically to protect plants from insects.

GENERAL PEST MANAGEMENT

Monitoring

Regular monitoring is the basis of all pest management programmes. A regular, weekly scouting programme should be conducted to detect problems at an early stage. Early detection and treatment lead to better pest control, since plant canopies are smaller and better spray coverage can be achieved.

Blue and yellow sticky cards

Use blue sticky cards to trap and detect adult stages of thrips and use yellow sticky cards for whiteflies and microlepidoptera. Place one to four cards per 100 m². The cards should be spaced equally throughout the greenhouse in a grid pattern with additional cards located near doorways and vents. Place some cards just above the plant canopy (to detect thrips and whiteflies). Inspect and replace the cards weekly to keep track of population trends.

Plant inspection

Plant inspection is needed to assess general plant health and to detect diseases, mites and aphids, plus any hot spots of immature whiteflies. Randomly select plants at ten locations in an area of 100 m², examining plants on each side of the aisle. Begin in a slightly different location each week, walking through the greenhouse in a zigzag pattern down the walkway. Examine the underside of leaves for insect pests and inspect root systems to determine whether they are healthy.

Key plants and indicator plants

Focus on scouting key plants and indicator plants:

- Key plants are plants or cultivars with serious, persistent problems every year. For example, peppers, tomatoes and eggplants are prone to aphid infestations: look for aphids on young leaves and for shiny honeydew on the upper leaf surface. If grown near flowering plants, peppers, tomatoes and eggplant will have signs of an early thrips population: look for distorted, young leaves with silvery flecked scars – signs of thrips feeding damage.
- Indicator plants are used to detect the presence of pests. For example, faba beans (*Vicia faba* L.) and certain petunia cultivars can detect the presence of thrips carrying TSWV. These plants will develop viral symptoms within one week if fed on by the infected thrips. The petunia cultivar ‘Summer Madness’ and several varieties of faba bean have been successfully used to detect tospoviruses.

Record-keeping and decision-making

Each time the crop is scouted, record the pest numbers, their location and the number of plants inspected. Records of pest numbers and locations will help identify population trends. Population trends are an indication of whether initial

Petunias and faba beans as indicator plants

- Remove flowers from indicator plants to encourage feeding on foliage where symptoms can be observed.
- Place a blue non-sticky card in each pot at plant height. The blue card will attract thrips to the indicator plant.
- Place petunia plants throughout the greenhouse among the crop at a rate of one plant every 6–9 m and faba bean plants at a rate of 12 pots per 100 m².
- Remove symptomatic leaves on petunia plants and continue to use the plants. The virus is not systemic in these plants. Thrips feeding injury leaves distinct white feeding scars on the foliage. Virus symptoms appear as a brown rim around the feeding scars.
- Remove entire plants of faba bean if symptoms are observed, because the virus is systemic in these plants. Viral symptoms appear as dark brown angular lesions on leaves or yellow to light green ring spots. Dark necrotic areas can also be seen on the stem. Faba beans have dark black spots on their stipules that should not be confused with viral symptoms.
- Replace with new plants, planting 1–2 bean seeds per 10-cm pot.

control measures were successful or need to be repeated. Once this information is collected each week, a pest management decision can be made. Monitoring and record-keeping help make the necessary treatment decisions by providing answers to the following questions:

- Is the population decreasing, increasing or stable over the growing season?
- Is spraying required?
- Are insects migrating from weeds under the benches to the crops?
- Is the previous week's treatment working?

Table 3 provides a list of selected means for managing diseases on greenhouse-grown vegetable transplants. Follow label instructions before using the material on vegetable plants. The product must be used only for crops for which the compound is registered.

Biological control for insects and mites

Biological control is an option for aphids, mites, fungus gnats, thrips, whiteflies and some lepidopters. Natural enemies are living organisms. They do not act as quickly as pesticides so cannot be used as “rescue” treatment. Natural enemies (parasitoids, predators of pathogens) are best used early in the cropping cycle when plants are small, pest numbers are low and damage is not yet observed. A detailed plan of action is needed to ensure success.

Accurately identify the key pests in the production system. Natural enemies, especially parasites, are often specific to a particular pest. Many insecticide residues can adversely affect natural enemies for up to 3 months after application.

TABLE 3

Selected insecticides labelled for insects and mites on vegetable plants

Insecticide	Target pests	Labelled crops	Comments
Azadirachtin	Many incl. aphids, thrips, caterpillars, leafhopper, leafminer, whitefly, mites	Many vegetables incl. curcubit, eggplant, tomato, peppers	Insect growth regulator for immature stages of insects. Repeat applications needed. Repels some insects and can be used as an antifeedant.
<i>Bacillus thuringiensis</i>	Certain caterpillars	Greenhouse vegetables, e.g. tomatoes, cole crops, peppers	Stomach poison that must be eaten by target insect to be effective. Most effective against small, newly hatched larvae. Insects stop feeding and die 1–5 days later.
<i>Beauveria bassiana</i>	Aphids, thrips, whitefly	Many vegetables incl. eggplant, peppers, squash	Contains a fungus that must contact target pest. Thorough spray coverage needed for contact material to be effective. Treat when insect population low. Repeated applications may be needed.
Fenazate	Spider mites	Many vegetables	Compatible with beneficial predatory mites. Rapidly degraded in high temperature alkaline water. Use solutions promptly or add a commercial buffering agent.
Buprofezin	Whitefly, leafhopper	Many vegetables	Active against nymph stages. Chitin synthesis inhibitor, suppresses oviposition of adults and reduces viability of eggs. Treated pests may remain alive for 3–7 days, but feeding damage is low. Apply no more than two applications per season.
Chlorfenapyr	Caterpillars, spider mites, broad mites, western flower thrips	Many vegetables – do not use on tomato varieties < 2.5 cm in diameter when mature	Do not apply more than 3 times during a crop cycle. Do not make more than 2 consecutive applications before rotating to a chemical in a different class.
Dinotefuran	Aphids, leafminer, thrips, whitefly	Vegetable transplants	Do not make more than one application per crop.
Imidacloprid	Aphids, leafhopper, leafminer, thrips, whitefly	Vegetable bedding	
Pyrethrins	Many incl. aphids, caterpillars, thrips, leafhopper, whitefly	Many vegetables	Flushes insects from hiding with knockdown effects.
Pyriproxyfen (distance insect growth regulator)	Whitefly, aphids	See supplemental label for indoor-grown fruiting vegetables Do not apply to tomato varieties < 2.5 cm in diameter or to non-bell peppers	Do not make more than 2 applications per season.
Spinosad	Leafminer, caterpillars, thrips	Many vegetables	See label for resistance management guidelines.
Spirotetramat	Aphids, spider mites, whitefly	Vegetable transplants	Will not control heavy population of spider mites.
Sucrose Octanoate Esters (SucraShield) 48 hr REI OMRI Listed	Aphids, caterpillars, leafhopper, mites, thrips, whitefly	Vegetables	Contact insecticide with limited residual activity.

Koppert and Biobest have compiled lists of insecticides and their effects on natural enemies (www.koppert.com and www.biobest.be, respectively). Farmers and extension staff must become familiar with insecticides compatible with natural enemies, for example, insecticidal soap, horticultural oil, insect growth regulators,

neem-based materials (azadirachtin) and other “physical kill” products (propylene glycol alginate) (see Table 3); a specific sprayer should be dedicated for their use.

Start in a small trial area (ideally, a separate greenhouse) to become familiar with the release, monitoring and evaluation of the effectiveness of natural enemies. Consult the supplier and a researcher to establish a schedule for the natural enemies’ introduction. Release rates and timing vary depending on the crop and its size, the degree of infestation, the effectiveness and the type of natural enemies, as well as the time of year. Starting a biological control programme will involve trial and error, as release rates have not been scientifically evaluated for vegetable plants. Vegetable plants with only one or two key insect pests or with a longer production schedule may be logical candidates for biological control. Natural enemies must be received from the supplier quickly (2–4 days) and kept cool during shipment; they should be inspected for viability and quality when received. Table 4 provides information on scouting for key pests and biological control options.

TABLE 4

Scouting guidelines and biological control options for vegetable plants

Pest	How to monitor	Where to look	Biological control options
Aphids	Monitor weekly. Rely on plant inspection, not sticky cards. Look for small, 1.5 mm long aphids with two cornicles or “tailpipes” at the rear of their body.	Underside of leaves and along stems on tips of new growth on eggplant, pepper, tomatoes and many different leafy vegetables. Signs of aphid activity: shed white skins, shiny honeydew, presence of ants, curled new leaves, and distorted growth.	<i>Aphidoletes aphidimyza</i> (aphid midge, predator) <i>Aphelinus abdominalis</i> (aphid parasite) <i>Aphidius matricariae</i> (aphid parasite) <i>Aphidius colemani</i> (aphid parasite) <i>Aphidius ervi</i> (aphid parasite) <i>Chrysoperla</i> spp. (green lacewing, predator) <i>Beauveria bassiana</i> (insecticidal fungus)
Bacterial leaf spot	At first, chocolate-brown spots are less than 6 mm in diameter, and water-soaked in appearance on pepper. Severely spotted leaves appear scorched and defoliation may occur. Some strains cause leaf spot on tomatoes.	Seed-borne disease. More prevalent during moderately high temperatures and long periods of high humidity and leaf wetness.	<i>Bacillus subtilis</i>
Botrytis blight	Look for leaf blight and tan stem cankers. Botrytis blight produces characteristic grey fuzzy appearing spores on the surface of infected tissues during humid conditions.	In areas where plants are spaced close together and where condensation may occur.	<i>Bacillus subtilis</i> (biofungicide) (suppression) <i>Streptomyces griseoviridis</i> (suppression) <i>S. lydicus</i> (suppression)
Broad mites	Look for symptoms of damage – leaf edges curling downward, twisted and distorted growth. Under a microscope, look on underside of leaves for mites and their eggs.	Near ornamental crops affected with broad mites.	<i>Neoseiulus californicus</i> (predatory mites) <i>N. cucumeris</i> (predatory mites)
Cyclamen mites	Look for symptoms of damage – inward curling of leaves, puckering and crinkling. Under a microscope, look within buds for mites and their eggs.		<i>Neoseiulus cucumeris</i> (predatory mites)

TABLE 4 (cont'd)

Scouting guidelines and biological control options for vegetable plants

Pest	How to monitor	Where to look	Biological control options
Damping-off (<i>Pythium</i> root and stem rot)	Visually examine roots for cortex that sloughs off leaving central core.	Inspect plants weekly for signs of disease: wilted, stunted off-colour plants with discoloured root systems. Focus on areas where plants stay wet or where there may be high populations of fungus gnats and shore flies that may carry disease spores. High soluble salts/fertility increases susceptibility.	<i>Bacillus subtilis</i> (biofungicide) <i>Trichoderma harzianum</i> (biofungicide) <i>Streptomyces griseoviridis</i> (biofungicide) <i>S. lydicus</i> (biofungicide)
Damping-off (<i>Rhizoctonia</i> root and crown rot)	Monitor seed flats of susceptible plants including cole crops, peppers and tomatoes. Look for small, water-soaked spots on stems or leaves before seedlings collapse.	Seed flats near walkways or near dust and debris. Overcrowded seedling flats are more susceptible to damping-off.	<i>Bacillus subtilis</i> (biofungicide) <i>Streptomyces griseoviridis</i> (biofungicide) <i>S. lydicus</i> (biofungicide) <i>Trichoderma harzianum</i> (biofungicide)
Powdery mildew	Scout weekly. Look for faint, white fungal threads and spores on leaves.	Scout near vents, or any location with a sharp change between day and night temperatures.	<i>Bacillus subtilis</i> (biofungicide) <i>Streptomyces griseoviridis</i> (biofungicide) <i>S. lydicus</i> (biofungicide)
Spider mites (two-spotted spider mites)	Rely on plant inspection. Look for light flecking, speckling or discoloured foliage, and webbing if high populations have developed.	Look in hot, dry locations in greenhouse (i.e. near furnace) or near entranceways.	<i>Amblyseius fallacis</i> (predatory mite) <i>Feltiella acarisuga</i> (predatory midge) <i>Neoseiulus californicus</i> (predatory mite) <i>Phytoseiulus persimilis</i> (predatory mite)
Thrips (western flower thrips)	Rely on sticky cards (placed just above crop canopy) and foliage inspection of key plants for early detection and to evaluate treatments. Use petunia and faba bean plants to indicate early thrips feeding.	Inspect plants by tapping tender new growth over a white sheet of paper. Watch for curled, emerging leaves, distorted new growth on pepper. Look for white scarring and black faecal spots on cucumber and eggplant.	<i>Amblyseius degenerans</i> (predatory mite) <i>A. swirskii</i> (predatory mite) <i>Chrysoperla</i> spp. (green lacewing, predator) <i>Hypoaspis miles</i> (predatory mite) <i>Neoseiulus cucumeris</i> (predatory mite) <i>Orius insidiosus</i> (pirate bug, predator) <i>Beauveria bassiana</i> (insecticidal fungus)
Tospovirus, <i>Impatiens</i> necrotic spot virus (INSV), Tomato spotted wilt virus (TSWV)	Symptoms vary depending upon the host. On pepper, look for necrotic spots on the leaf. Ring spots may also develop. On tomato, young leaves may develop small, dark brown spots.	Thrips populations may be highest at front and rear of the greenhouse. Use faba bean or petunia indicator plants to determine if thrips are carrying the virus. Symptomless weeds may also be a source of virus.	None See thrips
Whitefly	Rely on plant inspection to detect immature stages. Use sticky cards to monitor adults.	Egg-laying adults are found on the uppermost tender leaves of tomatoes, eggplant and assorted greens. Immature stages are stationary and are found on the undersides of leaves.	<i>Chrysoperla</i> spp. (green lacewing, predator) <i>Amblyseius swirskii</i> (predatory mite) <i>Delphastus catalinae</i> (predatory ladybeetle) <i>Eretmocerus eremicus</i> (whitefly parasite) <i>Eretmocerus mundus</i> (whitefly parasite) <i>Encarsia formosa</i> (whitefly parasite) <i>Beauveria bassiana</i> (insecticidal fungus)
Tomato borer	Sex pheromone traps.	Check the traps and the first appearance of mines on the plant.	<i>Bacillus thuringiensis</i> , <i>Nesidiocoris tenuis</i> , <i>Trichogramma</i> spp.

SPECIFIC INSECT PESTS AND MITES

Common insect pests on vegetable plants include aphids, fungus gnats, shore flies, whiteflies, thrips, two-spotted spider mites and Lepidoptera. There follows a brief description of the major pests, including their life cycle and monitoring tips. See Tables 1 and 4 for additional scouting guidelines, registered pesticides and biological control options.

Aphids

Life cycle

Several species of aphid can occur on vegetable transplants, but the most common are green peach, melon and foxglove. Aphids are small, 1.5 mm in length, round, soft-bodied insects, varying in colour from light green to pink or black. The green peach aphid is yellowish-green in summer, pink or yellowish in autumn and spring. Winged forms are brown with a large dusky blotch on the abdomen. Melon aphids are greenish-yellow to very dark green with black mottling and short dark cornicles (tubular structures on the posterior part of the abdomen). Foxglove aphids are smaller than potato aphids but larger than melon and green peach aphids. The foxglove aphid is a shiny light yellowish green to dark green with a pear-shaped body. The only markings on the bodies of wingless adults are dark green patches at the base of the cornicle. The legs and antennae also have black markings. Foxglove aphids cause more leaf distortion than green peach or melon aphids. Aphids feed by inserting their piercing, sucking mouth parts into the plant tissue and removing fluids. In greenhouses, aphids are usually females that produce live young called nymphs. Each female can produce 50 or more nymphs. Nymphs mature to adulthood and begin reproducing in as little as 7–10 days. Adults are usually wingless, but some produce wings when populations reach outbreak levels. Large numbers of aphids stunt and deform plants. In addition, aphids produce a sticky digestive by-product called honeydew, which can cover leaves and provide a food source for a superficial black fungus known as sooty mould. Aphids are present on weeds and may enter the greenhouse through vents.

Monitoring

Examine the foliage, stems and new growth of key plants such as peppers, eggplants, cole crops and leafy greens for early detection of aphid infestation. Signs of aphid activity include shedding of white skins, shiny honeydew, curled new leaves, distorted growth and the presence of ants. Yellow sticky cards help detect the entrance of winged aphids into the greenhouse from outdoors. Yellow cards will not, however, permit the monitoring of aphids within the crop, as most of the aphids will be wingless.

Whiteflies

Life cycle

The silverleaf whitefly (*Bemisia argentifolii*) and greenhouse whitefly (*Trialeurodes vaporariorum*) may infest vegetable plants; greenhouse whitefly is the most

common species. Both adult and immature whiteflies have piercing sucking mouthparts, are able to remove fluids and produce honeydew resulting in sooty mould fungus. Winged adult whiteflies are 1.5 mm in length and are found on the undersides of the youngest, most tender leaves. Females may lay 150–300 eggs, which hatch into first-instar nymphs in about a week. The crawlers move for a short distance before settling down to feed. After three moults, there is the pupa stage, from which adults emerge in about 6 days. Whiteflies complete their egg-to-adult cycle in 21–36 days depending on greenhouse temperature.

Monitoring

To monitor whiteflies, check susceptible plants, such as tomatoes, at ten locations in an area of 100 m², examining plants on each side of the aisle. Look on the undersides of one or two leaves per plant, for nymphs, pupa and adults. Yellow sticky traps can also be used to detect adult whiteflies once populations have reached higher densities. Begin treatments as soon as the first sign of infestation is noted.

Thrips

Life cycle

The most injurious species is the western flower thrip (WFT); the pests often do considerable damage before being discovered, because they are small, multiply rapidly and feed in plant buds in which they can remain undetected. WFT also vector tospoviruses. Feeding marks from the rasping mouth parts of thrips appear as white streaks on the leaves. Infested new growth may curl under and leaves are often deformed. Adult WFT are about 1.5 mm long, with narrow bodies and fringed wings. Females are reddish brown and males are light tan to yellow. The immature stages are light yellow. Female thrips insert eggs (several hundred per female) into plant tissue. The tiny yellowish larvae moult twice and feed on plant fluids as they mature. Larvae drop off the plant into the soil and pass through two stages, after which adults emerge. The egg-to-adult life cycle can be completed in 7–13 days depending on greenhouse temperature: development is more rapid under warm temperatures than under cool temperatures.

Monitoring

Early detection of a thrips infestation is critical for effective management because populations are lower and it is easier to obtain good coverage when plant canopies are small. Symptoms of feeding are often not noticed until the damage has occurred. Eggplant, tomatoes and peppers are especially prone to thrips infestations. Blue sticky cards, key plants and indicator plants are all effective for the detection of onset of an infestation. Yellow sticky cards should be placed just above the crop canopy, near doors and vents, and over thrip-sensitive cultivars to monitor the movement of the thrips. Recent research has shown that light to medium-blue sticky cards catch more thrips than yellow ones. However, it is more practical to use yellow cards for general pest monitoring to attract fungus gnats,

whiteflies and winged aphids. The number of thrips per card should be recorded and graphed weekly to monitor population levels and movement in or out of the greenhouse, and thus help make control decisions.

Tomato borer

Life cycle

Tomato borer, *Tuta absoluta*, reproduces rapidly, with a life cycle of 24–38 days, depending on temperature. The minimum temperature for activity is 9 °C. The larval stage (caterpillar) does not enter diapause while food is available. During the life of one female, up to 250 eggs may be deposited on above-ground parts. Eggs hatch and the caterpillars mine inside the leaf, stem or fruit. There are four larval stages completed within 2–3 weeks. Pupation may take place in the soil or on the surface of a leaf, in a curled leaf or in a mine. The moths are active at night and hide between leaves during the day.

The tomato borer came to the Near East region in 2006 and can cause extensive damage; it has a strong preference for tomato and can cause 50–100 percent yield reduction. Larvae can infest any part of the plant above the ground at any stage of the crop. The most distinctive symptoms are the blotch-shaped mines in the leaves; in the case of serious infection, leaves die off completely. Damage to fruits allows fungal diseases to enter, leading to rotting fruit before or after harvest.

Monitoring

Use special sex pheromone traps to detect the first presence of the moth inside and outside the greenhouse. Check plants for the first appearance of mines.

Spider mites

Life cycle

Two-spotted spider mites can be found on vegetable plants. Adult females are approximately 0.5 mm long, and slightly orange in colour. All mobile stages are able to pierce plant tissue with their mouth parts and remove plant fluids. Most spider mites are found on the underside of leaves. Feeding injury often gives leaf surfaces a mottled or speckled, dull appearance. Leaves then turn yellow and drop. Large populations produce visible webbing that can completely cover the leaves. Eggs are laid singly, up to 100 per female, during her 3–4-week life span; they then hatch into larvae in as few as 3 days. Following a brief larval stage, several nymphal stages occur before adults appear. The egg-to-adult cycle can be completed in 7–14 days depending upon temperature. Hot and dry conditions favour spider mite development.

Monitoring

Mites often develop as localized infestations on particular groups of plants such as beans, tomatoes or eggplants. Adult mites are not found on sticky cards and it is necessary to examine foliage to check for the presence of mites: turn over the

leaves of sample plants and, with a hands-free magnifier (Optivisor) or hand lens, check for the presence of spider mites.

Cyclamen mites

Life cycle

Shiny, orange-tinted cyclamen mites prefer to hide in buds or deep within flowers. Adult females can lay 2–3 eggs per day for up to 2–3 weeks. Eggs are deposited in moist places at the base of the plant. Cyclamen mites can complete their life cycle in 1–3 weeks. Females can live up to 1 month and can reproduce without mating. Cyclamen mite females lay 2–3 eggs per day for up to 2–3 weeks. Cyclamen mite eggs are oval, smooth and about half the size of the adult female. Larvae hatch from the eggs in 3–7 days. The slow-moving white larvae feed for 4–7 days. Cyclamen mites prefer high relative humidity and temperatures of 15 °C. Cyclamen mites feed upon many ornamental bedding plants including dahlia, fuchsia, gerbera daisy, petunias and viola, as well as strawberries in the field. They may migrate to peppers or tomatoes.

Monitoring

Cyclamen mites pierce tissue with their mouth parts and suck out the cell contents. Signs of damage may be concentrated near the buds or over the entire plant. Symptoms include inward curling of the leaves, puckering and crinkling. Pit-like depressions may develop. The mite is only 0.25 mm long and examination under a microscope is often needed to confirm the presence of cyclamen mites.

Broad mites

Life cycle

Broad mites are closely related to cyclamen mites. They can be distinguished from cyclamen mites in their egg stage. Eggs are covered with bumps that look like a row of diamonds and they are best seen using a dissecting microscope. Adults and larvae are smaller than cyclamen mites and walk rapidly on the underside of leaves. Broad mites can also attach themselves to whiteflies and use the whiteflies as a carrier for their dispersal. The development of broad mites is favoured by high temperatures (21–26 °C). Broad mites can complete their life cycle in as little as 1 week. Females lay 30–75 eggs.

Monitoring

Broad mites can affect various ornamentals, including gerbera daisy, New Guinea Impatiens, salvia, ivy, verbena and zinnia, and may migrate to peppers or tomatoes. Characteristic damage includes leaf edges curling downwards or dying terminal buds. As they feed, broad mites inject toxic saliva, resulting in twisted, distorted growth. Broad mite injury should not be confused with herbicide injury, nutritional (boron) deficiencies or physiological disorders. Inspect the underside of the leaves with a 20× hand lens for the mites and their eggs.

Advantages of IPM

- Limited disruption of natural beneficial insects
- Few hazards to human health
- Minimal negative impact on non-target organisms
- Limited environmental damage
- Optimal preservation of natural and managed ecosystems
- Long-term reductions in pest control requirements
- Effective implementation operationally feasible
- Cost efficiency in short and long term

IPM support services and tools

- Record-keeping and monitoring system of the target pest
- Alternative methods assessed and/or implemented
- Management guidelines, procedures and standards
- Pest management strategies
- IPM implementation timetables, plans and cost estimates
- Farmer education and training

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16. Integrated pest management

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INTRODUCTION

This chapter discusses aspects of integrated pest management as part of GAP, highlighting cultural techniques relevant to pest and disease management (at nursery level and in the production greenhouse), physical control, mechanical control, general hygiene and specific sanitary measures, host plant resistance, greenhouse worker training, crop and pest monitoring, and biological and chemical control of pests and diseases. Finally, general guidelines are provided with recommendations regarding successful application of an IPM programme in line with GAP standards.

Pest and disease control is probably the greenhouse crop practice with the greatest impact not only on the environment and human health, but also on public opinion in recent years. As agriculture under protected cultivation develops, plants become more susceptible to pests for several reasons, including monoculture cultivation and the use of selected, high-yielding varieties which sometimes stimulate pest and disease development. Various control methods have been developed and new methods incorporated into the production system. Control methods may be classified as non-chemical or chemical, as preventive or curative. Most frequently used methods:

- Cultural control: adoption of cultural practices during crop production.
- Host plant resistance: use of a plant's capacity to avoid or repel attack by pests (cultivar or rootstock).
- Biological control: use of living organisms (insect and mite predators, insect and nematode parasitoids, microbial agents [viruses, bacteria, fungi etc.]).
- Other biologically based control: use of chemical stimuli (pheromones) or plant extracts.
- Mechanical control: use of insect nets as mechanical barriers, colour sticky bands or light traps.
- Physical control: exploitation of solar heat energy to destroy pests in the greenhouse environment, in both soil and substrates.
- Chemical control: use of synthetic and non-synthetic chemical compounds.

IPM

IPM as defined by FAO, is an ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimize the use of pesticides.

FAO promotes IPM as the preferred approach to crop protection and regards it as a pillar of both sustainable intensification of crop production and pesticide risk reduction. As such, IPM is being mainstreamed in FAO activities involving crop production and protection.

The FAO IPM programme currently comprises three regional programmes (Asia, Near East and West Africa) and several stand-alone national projects. Under these programmes and projects, FAO provides assistance in capacity-building and policy reform, and facilitates collaboration among ongoing national IPM programmes.

During the past 60 years, pest control has been based largely on the use of synthetic chemical pesticides, but the beginning of the twenty-first century saw a major change in crop protection, with biologically based technologies replacing or used in integration with conventional synthetic chemical pesticides. Some biologically based technologies already account for a significant part of the crop protection market, particularly with regard to host-plant resistance to pests and diseases and biological control. This approach – using other control measures instead of only relying on chemical control – is known as integrated pest management (IPM).

In 1997, the concept was extended to “integrated production and pest management” (IPPM), incorporating a range of practices: crop rotation, cultivation, fertilization, pesticide use, cultural control measures, biological control and other alternatives to conventional chemical control. IPPM is a sustainable, environmentally and economically justifiable system: damage caused by pests, diseases and weeds is prevented by natural factors and adoption of good agricultural practices (GAP), limiting population growth of these organisms and, where necessary, including also appropriate control measures.

IPM in protected cultivation

The occurrence, development and control of pests and diseases under greenhouse structures is undoubtedly influenced by the fact that the crops are enclosed. The complex control systems of modern greenhouses are designed to maintain an ideal environment for the crop, both economically and physiologically. These conditions also provide a protected, favourable environment for pests and pathogens: optimal humidity and temperature, no rain and no wind. Pests and pathogens may therefore be more prolific and cause more damage to their hosts

in greenhouses than in open field conditions. Moreover, compared with open field cultivation, natural enemies may be scarce or entirely absent, unless accidentally or purposefully introduced; on the other hand, the stability of the greenhouse environment allows natural enemies of pests to be used as an effective means of control.

As crop cultivation methods become more advanced, pest and disease control must evolve accordingly. A number of radical new systems for growing plants (e.g. soilless systems) have been introduced in recent years. When a cultivation method changes, pest and disease organisms become exposed to a new ecosystem. This in turn may require changes to be made in the traditional methods of control. There are other reasons why greenhouses require exceptional crop protection measures. Rotation cannot normally be practised in greenhouses, due to economic factors related to the high level of expertise required for commercial success. Consequently, the same crop or crops are grown year after year; particular care must therefore be exercised, especially regarding pests which persist in the soil or on the structure of the greenhouse itself.

As the value of greenhouse crops is usually high, expensive control measures may be economically justified to achieve the high standards of pest and disease control required. In general, when choosing and applying pesticides for greenhouse crops, greater care is required to avoid phytotoxic effects or pesticide residues. Chemical control may easily be applied in prophylactic treatments when a clean crop is needed (e.g. ornamentals). Ornamentals have a high aesthetic value and a damaged flower is unstable; they lose their value even at a low level of infestation or when exported to countries with zero-tolerance regulations for certain pest organisms. With most other crops, however, some infestation can usually be tolerated, as it leads to little or no damage.

At present, IPM is seen as the standard for modern crop protection technology. Compared with other sectors, more of the new, non-chemical control techniques are already being used in greenhouses as part of IPM programmes. A multifaceted approach to greenhouse crop protection, with integration of chemical, cultural, biological, mechanical and physical control of pests and diseases, will be more successful and make adaptive changes in pests and pathogens less likely. In northern Europe, IPM is currently used in over 95 percent of greenhouse vegetable and ornamental production area. In the particular case of Morocco, IPM adoption in greenhouse vegetable farms has increased from 5 ha in 1999 to 4 230 ha in 2011. In terms of the percentage of greenhouse area adopting IPM in Morocco, tomato is by far the leading crop (61.4%), followed by pepper (22.4%), strawberries (10.6%) and green beans (2.6%). The biological control of insects and mites has resulted in a significant reduction (over 60%) in pesticide use. IPM has become the general crop protection policy in greenhouse crops, and is the wise answer to the overuse of chemical pesticides.

PREVENTIVE MEASURES

A wide range of reduction methods may be applied, depending on the type of crop and the region of production. Before the emergence of chemical control, cultural control was important in greenhouse crop protection. Today, growers are so specialized that important cultural control methods such as crop rotation are not popular in protected crops. Moreover, methods such as mixed cropping, multiple and intercropping and trap cropping are seldom used in greenhouses. Prevention of pest introduction and mechanical/physical control may be considered part of cultural control, and these practices are often applied in greenhouses. Mechanical control was initially based on the removal of weeds and infested parts of plants (e.g. removal of mines with leafminer larvae). In recent years, however, it has come to include use of fine mesh insect nets on all aeration openings of the greenhouse as well as the establishment of safety access systems (SAS) for the exclusion of pests and vectors. Physical control is applied to disinfect the soil. Another form of cultural control is the management of the crop's environment to prevent or reduce diseases through computer models designed to predict the optimal greenhouse climate for production of a crop while taking disease control into account.

Host plant resistance to disease is widely used; plant resistance to insects and nematodes is increasingly the focus of research and development. While it can be impossible to eradicate a recently invasive pest and the costs involved are very high, eradication is still easier in the greenhouse than in the open field.

Inspection and quarantine

Pests evolve to their fullest extent in the centres of origin of specific crop plants. Many pests are, therefore, localized in specific areas, and it is in the general interest of agriculture to limit their distribution. Crop species sometimes extend to new areas initially unaccompanied by many of their pests and pathogens, and these crops therefore produce well in the new areas. However, much of this advantage is slowly lost as pests and pathogens tend to follow the crop sooner or later.

In order to prevent or diminish the risk of exotic pest species becoming endemic, there are extensive rules and guidelines concerning the health conditions of imported plant material. Control of pests and diseases through legislation is extremely important and health certificates are required by plant protection services in many countries.

Measures at greenhouse level

In greenhouses, rotavators are used to prepare the soil: they produce very fine soil particles, resulting in high germination of weed seeds. Black and white plastic mulching – whether applied locally (localized mulching) on rows or all over the ground of the greenhouse (total mulching) – is an important way of controlling weeds and some insect pests (thrips, leafminers etc.). Other sanitary measures during the growing period include removal by hand before the weeds set seed.

**Plate 1**

Example of complete mulching of the greenhouse floor preventing weeds and acting as mechanical barrier to certain insect (leafminers, thrips, Tuta absoluta and other lepidopteran pests) life stages preventing them from moving to the soil for pupation (life cycle interruption)

**Plate 2**

On-row mulching preventing weed competition for nutrients with the crop

Preventive measures (for the subsequent crop) may be taken at the end of the previous crop cycle, using solarization to reduce pest and disease inoculums in the soil. After several years of complete prevention, infestation becomes very low, and pest and pathogen inoculums in the soil decrease to manageable levels.

HOST PLANT RESISTANCE

Plants in their natural environment can adapt to diverse abiotic and biotic factors, for example, high altitudes (abiotic stresses) and herbivory or diseases (biotic stresses). Resistance may be based on different mechanisms: antixenosis (characteristics deterring/reducing colonization by herbivores) or antibiosis (characteristics leading to the killing or reduction of herbivores after landing and during eating).

Breeding for improved quality and higher yields has been practised for centuries. In the past, seeds were purposefully harvested from plants with fewer symptoms of diseases or pests, resulting in some level of field resistance. Today, commercial breeding's interest in enhanced production and cultural quality, combined with the use of pesticides on the selection fields, has resulted in susceptible varieties. Host-plant resistance against insects still requires further development, while resistance against diseases is already highly developed for many cultivars.

The use of disease-resistant cultivars is, in theory, the easiest and most convenient way to achieve disease control; ideally, cultivars should be resistant to all the crop's diseases. In reality, however, there are very few crops where even a small proportion of the cultivars are resistant to more than a small number of diseases. Tomato is one of these: over 70 diseases are known to occur in tomato and there are some cultivars resistant to just four of them – tomato mosaic virus (TMV), leaf mould, *Verticillium* wilt and *Fusarium* wilt. Unfortunately, many

pathogens exist as strains, each with different virulence genes, so that a cultivar may be resistant or tolerant to some but not all strains of the pathogen.

Resistant cultivars usually remain disease-free for only a short time, because more new strains of the pathogen evolve, or because the pathogen population is a mixture of many different strains with one or more predominating at any one time. The balance of strains of the pathogen often responds quickly to changes in the host population. It is difficult, if not impossible, to determine whether a pathogen population is a mixture of different strains with some present in extremely low proportions or whether the pathogen produces virulent mutants at infrequent intervals which are normally lost from the population unless there is a suitable resistant host present on which they can grow. Sometimes such mutants, although able to grow on resistant cultivars, are not as able to compete with other strains and do not survive because they are less fit. But for various reasons, some newly introduced resistant cultivars rapidly lose their resistance.

A more logical approach, albeit more difficult and time consuming, is to combine as many genes as possible into each cultivar. Resistance of this type will only break down if the pathogen produces a complex race capable of overcoming all the resistant genes at once. Some plant breeders have followed this approach by combining all the known sources of TMV resistance into tomato cultivars. These cultivars have been grown commercially for a number of years and so far no TMV strain capable of overcoming their resistance has been found.

Resistance as an IPM component remains the most effective way of combating viral diseases. Resistant varieties exist for a number of viruses. However, complete and durable resistance is difficult to achieve in breeding programmes.

Nevertheless, pests and diseases may adapt to host plant resistance, a process comparable to the adaptation of pests to pesticides. In particular, adaptation occurs when resistance is high, inheritance is simple, and the resistant cultivar is grown widely. Therefore, knowledge about the variability of the pest or pathogen species involved is necessary. Fortunately, resistance to insects often tends to be partial and its inheritance polygenic, so that selection of biotypes adapted to resistance is less likely. However, recent developments in resistance breeding, such as the breeding of transgenic plants carrying toxic genes from *Bacillus thuringiensis*, tend to focus on monogenic factors with a very high expression.

BIOLOGICAL CONTROL OF INSECTS AND MITE PESTS

This section deals with some general issues concerning biocontrol: what is biocontrol, why is it needed, what types of organisms are used as control agents, and what methods of biocontrol exist? A biological control project plan is presented, as well as a procedure to evaluate natural enemies prior to their introduction.

The emphasis is on insects and mites as target organisms for biological control. The principles of biological control for plant pathogens are outlined where they differ from insects and mites; other pest organisms (nematodes, viruses and weeds) are treated only briefly as development in these areas, at least for greenhouse crops, is lagging behind.

Definition

The term “biological control” has been applied to include virtually all pest control measures excluding the application of chemical pesticides. Nowadays, however, it is generally agreed that the term should be defined as “the use of living organisms as pest control agents”, implying human intervention.

- Natural control: in nature, potential pests are kept at low densities by their natural enemies.
- Biological control: natural enemies are relatively large organisms (e.g. spiders, predatory bugs or parasitic wasps).
- Microbial control: natural enemies are micro-organisms (e.g. bacteria, fungi, protozoa, nematodes or viruses).
- Biotechnical control: pheromonal attraction, genetic control with the sterile male technique, chemical control with juvenile hormones and host-plant resistance are all biotechnical techniques.

The term biotechnical control is similar to biorational or biologically based control. Genetic control and control with attractants, repellents, anti-feedants and pheromones (a special category of attractants) are not commonly used in greenhouses.

History of biological control in greenhouse crops

Successful greenhouse production requires well-trained growers who are not prepared to risk damage from insects for ideological reasons: if chemical control works better and is cheaper they will certainly use it. Despite this, biological pest control has been applied in greenhouses with commercial success for about 45 years. Growers readily accepted its introduction and now rely on it. The main reason for the rapid development of biological control methods was the occurrence of resistance against pesticides in several key greenhouse pests.

In the past 45 years, over 30 species of natural enemies have been introduced against more than 22 pest species. The greenhouse area on which biological control is applied has increased from 400 ha in 1970 to over 50 000 ha today. Biological control of key pests in greenhouses is currently applied in more than 25 countries out of a total of 35 countries with a greenhouse industry.

Biological and microbial control agents

Modern biological control depends on the use of specific natural enemies of the target pest, carefully selected and screened to eliminate species which could pose a threat to other useful organisms.

Predators

Individual predators consume a number of prey during their lifetime and actively seek their food. Some species are polyphagous and consume a wide range of prey; others are oligaphagous (narrow range) or monophagous (extreme specialists). Polyphagous arthropod predators do not concentrate their attention on target pests and tend to feed on the most abundant and easily captured prey. Monophagous and oligaphagous predators are more likely to be suitable for biological control. Many different species of predators are used in greenhouse biological control programmes.

Parasitoids

These insects (many of which are monophagous) develop parasitically in a single host which is eventually killed. They include a remarkably diverse group of small wasps and flies, with about 300 000 described species. The adults are free-living and highly mobile, and can actively search for hosts in/on which to lay eggs. The larvae live in (endoparasitoid) or on a host (ectoparasitoid) until they are fully grown (egg, larvae and pupal stage); they generally kill their host at the moment of pupation. A number of parasitoid species are used for pest control in greenhouses.

Pathogens

Parasitic micro-organisms will often kill their host outright. Dead hosts liberate millions of individual microbes, which are dispersed by the wind and vectors. With protozoans, the effect on pests is generally more long term. Pathogens are easily mass-produced, and release methods are similar to the application of chemical pesticides.

Bacteria

Almost all bacteria in microbial insecticides currently in production are species of the genus *Bacillus*. There are other bacteria which are pathogenic to insects, but they are also potentially harmful to man or difficult to mass produce. In most cases, bacteria affect their hosts after being ingested with food, often producing toxic metabolites that damage the gut wall. The best known and most successful species is *B. thuringiensis* (*Bt*). The time from ingestion of a lethal dose to death varies from hours to one or two days. However, even at sublethal doses, the insect stops feeding within hours. Its toxin is extensively used in greenhouse biocontrol to control caterpillars, and has been involved in the development of several transgenic plants (essentially field crops) with resistance to key lepidopteran and coleopteran pests.

Viruses

Viruses are not free-living and can only replicate in living host cells. There are at least seven families of viruses containing insect-pathogenic representatives. The Baculoviridae family is unique in that it is exclusive to invertebrates and they bear no resemblance, structural or biochemical, to invertebrate pathogens. In terms of safety and thanks to their pesticidal potential, Baculoviruses are particularly suitable for biological control. Baculoviridae can be applied to control insect pests caused by the larvae of Lepidoptera. The larvae die 4–8 days after infection, and millions of virus particles are set free by the putrefying cadaver. In greenhouses, an NPV (nuclear polyhedrosis virus) is used to control larvae of *Spodoptera exigua*. Although many of these viruses are rapidly inactivated by UV radiation between 280 and 320 nm, this portion of the light spectrum is absorbed by glass and plastic sheet, and the application of viruses can be very successful in greenhouses.

Fungi

Fungi are the only insect pathogens capable of invading the insect by penetrating the cuticle – the most common means of infection. Therefore, those insects that feed by sucking, such as aphids and scales, are attacked only by fungal pathogens. As a result, fungi are very dependent on environmental conditions, in particular high humidity, to achieve infection. Most fungi successes have been with Deuteromycetes, which cause epizootic on foliage-feeding insects in tropical environments only. In greenhouses, two fungal products are applied against whiteflies: *Verticillium lecanii* and *Aschersonia aleyrodalis*; the more general fungus, *V. Lecanii*, is also used for control of aphids and thrips.

Nematodes

The most promising nematodes belong to the family Steinernematidae – *Heterorhabditis* and *Steinernema* (*Neoplectana*). They are characterized by their association with a bacteria of the *Xenorhabdus* genus. The infective juveniles carry mutualistic bacteria in their intestines, and on entering the insect host (through natural openings), they release the bacterial cells that propagate and kill the insect within 48 hours. These nematodes are virulent, kill hosts quickly and are easily mass-produced *in vivo* and *in vitro*; they have a very broad host range. Both groups are used in greenhouse biocontrol programmes.

Methods of release of biological agents

Parasitoids, predators and pathogens can be used in different types of biological control programmes, described below.

Inoculative biological control

Beneficial organisms are collected in an exploration area and introduced and released (in limited numbers only) where there is a pest occurrence. The method aims for long-term suppression of pest populations and is typically used against introduced pests, presumed to have arrived in a new area without their

**Plate 3**

Inundative release of Amblyseius swirski in a soilless pepper crop early in the season

natural enemies (which are then sought in the pest's area of origin). The first widely practised form of biological control, it is also known as "classical" biological control. No examples exist for greenhouse crops, as permanent biocontrol is impossible in protected cultivation: the crop, its pests and natural enemies are removed from the structure at the end of each growing season.

Inundative biological control

Indigenous or exotic beneficial organisms are mass-reared in the laboratory or acquired from specialized biological control

companies and periodically released in large numbers in order to obtain immediate control of pests for one or two generations (i.e. use as biotic insecticide), with no anticipation of the potential effects on subsequent generations. An example of this approach is the frequent application of high numbers of predatory mites (*Amblyseius* spp.) against thrips (*Frankliniella* sp.) in protected cultivation.

Seasonal inoculative biological control

Native or exotic natural enemies are mass reared or acquired from the international market and periodically released in short-term crops (3–10 months) against pests, and the control effects are expected to last several generations. A large number of natural enemies are released – for an immediate control effect, plus a buildup of the natural enemy population for control later in the season. This method is essentially different from inundative control, because it aims to achieve a control effect over several generations and therefore resembles inoculative control. An illustration of this technique is the biological control of the recently introduced invasive species *Tuta absoluta* to Europe (2006), North Africa (2008) and the Near East (2009–10), with the exotic (originally from Latin America) parasitic wasp *Trichogramma achaeae*.

Conservation

Conservation is an indirect method where measures are taken to conserve natural enemies; it may result in a richer diversity of beneficial species as well as in larger populations of each species, leading to better control of pests. For example, where parasitoids of leafminers and aphids occur naturally in the fields surrounding greenhouses, they may immigrate into protected structures and give adequate control. Proper management of the crops and the surroundings of greenhouses may therefore stimulate or restore natural control.

How to implement a biological control programme

Planning the biological control programme

A programme description is made, in which both the taxonomic and the noxious status of the target organism (pest animal or weed) are defined. Information is collected, through literature research and correspondence, concerning the biology of the pest and its natural enemies. If an appropriate natural enemy is not available in the international market, exploration is undertaken and an inventory of natural enemies started, with attention to aspects of genetic diversity of the natural enemy and collection of a sufficient quantity of specimens.

A natural enemy's importance in the exploration area is determined by studying host range and negative characteristics (e.g. hyperparasitic habits, polyphagy). On the basis of these data, an initial selection can be made of species for future studies. Although studies in the exploration area cannot usually be relied on to predict whether or not a new natural enemy species will become established or effective in a new environment, they help discover whether an agent is clearly unsuitable for particular areas. Following initial selection, a detailed study is carried out of the promising species. The selected material is prepared for shipment, and the natural enemy is mass produced and released in the country where the pest is to be controlled. A final evaluation of the effectiveness should then be executed in the target area.

Shipment of natural enemies

Entomophagous insects and mites can be brought into the greenhouse in different stages of their development:

- eggs (e.g. *Chrysoperla*)
- larvae or nymphs (e.g. *Orius*, *Phytoseiulus*)
- pupae (e.g. *Trichogramma*, *Encarsia*, *Eretmocerus*)
- adults (e.g. *Aphidius*, *Diglyphus*)
- all stages (e.g. *Amblyseius*)



Plate 4

*Container card (capsule) (5 000 eggs of *Ephestia khuniella* parasitized with the parasitoid *Trichogramma achaeae*), used in biological programme of *Tuta absoluta* in Saudi Arabia (FAO Projects UTF/SAU/025 and 038/SAU) in collaboration with BIOTOP France*

**Plate 5**

Release of Nesidiocoris tenuis with additional food supplement (Ephestia eggs) (FAO Projects UTF/SAU/025 and 038/SAU, Saudi Arabia)

The stage at which they are introduced depends mainly on transportation and manipulation in the greenhouse; transport and release often take place when they are least vulnerable to mechanical handling, i.e. the egg or pupal stage. When it is difficult, but essential, to distinguish the natural enemy from the pest (host), the only solution is to introduce adults. Release of adult parasitoids is not recommended as handling and release are extremely difficult, often resulting in a reduction in fertility compared with parasitoids released when immature.

Release of natural enemies

There are a variety of methods for introduction in the greenhouse. Eggs and pupae may be distributed over the greenhouse on their normal substrate (leaves of the host plant, e.g. *Chrysoperla* and *Encarsia*) or glued on paper or cardboard cards (e.g. *Encarsia*, *Trichogramma*, *Eretmocerus*). At these stages, natural enemies can also be collected and put into containers, which are then brought into the greenhouse (e.g. *Nesidiocoris*).

Natural enemies at a mobile stage (larvae, nymphs or adults) can be placed in the greenhouse in containers (e.g. many adult parasitoids and predators) or the grower can distribute or sprinkle them over the plants. Biological control companies, distributors and extension services should be consulted for advice concerning: correct handling (especially after pick-up from airport on arrival of shipment); timely delivery (time between airport and farm delivery); and release (practical handling of containers) of the beneficial insects. However, in countries only recently adopting this technology, sufficient advice on biological control applications is seldom available – a weak point in the chain of biological control.

Risks of biological control

Current knowledge indicates that the negative effects of chemical pesticide use outweigh the risks associated with biological control. The risks of using natural enemies for pest control are nevertheless discussed here.

Environmental risks

No insect natural enemies used for biological control of insect pests are directly harmful to humans. They may, however, create risks for the environment (e.g. attacking other useful organisms). Many species are transferred from one world region to another. Although potential natural enemies are screened for possible negative effects in the area of introduction, it can never be predicted with absolute

certainty that a natural enemy will not change its behaviour and attack other beneficial organisms or innocuous inhabitants of the same environment.

No cases are known of insect natural enemies changing host spectrum after reducing the pest population to levels much below that of economic importance. Usually, low populations of natural enemy and host result and co-exist for long periods. The special dietary requirements and behaviour of natural enemies virtually exclude the possibility of them becoming pests themselves (with the exception of some natural enemies, e.g. *Nesidiocoris tenuis*, which can cause tomato fruit damage at high population levels towards the end of the crop cycle).

Risks of resistance

With regard to resistance, several defence mechanisms exist for a host to escape from parasitism or predation. Besides behavioural defence (searching for a hiding place, strong body movements to prevent attack, spitting etc.) and morphological defence (e.g. development of a thick cuticle), many host species possess an internal defence mechanism against parasitoids: the encapsulation of parasitoid eggs. The development of complete host resistance towards a parasitoid species is extremely rare in biological control, although encapsulation occurs widely among many groups of insects.

The frequent development by pests of resistance to insecticide compounds is a phenomenon which has not been observed in natural enemies during the past 45 years. It is presumed that the co-evolution of natural enemies and hosts will prevent development of complete resistance of pests to their enemies. Under strong parasitoid pressure, there is constant host selection for the capability to encapsulate parasitoid eggs. There is also constant selection for parasitoids with the ability to escape from encapsulation. This reciprocal selection process does not, of course, exist in a pesticide–host relationship.

PRACTICAL BIOLOGICAL CONTROL OF INSECTS AND MITES

Biological control, including seasonal inoculative releases and techniques to increase and conserve natural enemies, is used against major greenhouse pests and some diseases. The decision threshold and the rate of natural enemies required for the control of different pests are generally provided by companies that commercialize biological control agents.

Whiteflies

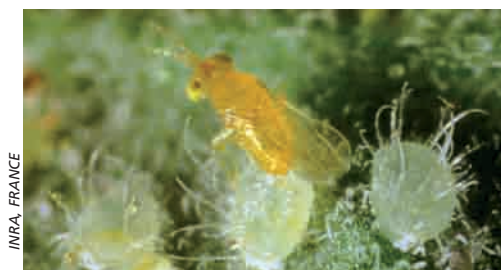
Biological control of *T. vaporariorum* with seasonal inoculative releases of the parasitoid, *Encarsia formosa*, is widely used in greenhouses in temperate areas and to a lesser extent in warmer regions. However,



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Plate 6

Adult Macrolophus caliginosus

**Plate 7**

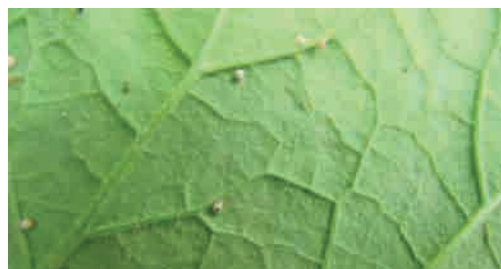
The adult parasitoid Eretmocerus sp. parasitizing a whitefly pupa

**Plate 8**

Adult Bemisia tabaci – a vector of over 30 plant viruses of greenhouse crops

**Plate 9**

Adults of the parasitoid Diglyphus isae, immediately after release in the greenhouse for biological control of leafminers

**Plate 10**

Mummies of the insect pest Aphis gossypii, parasitized with the parasitoid Aphidius colemani, released earlier in the season

E. formosa is not very efficient under cool, cloudy conditions, and inoculative release of the predator, *Macrolophus caliginosus*, is a complementary measure. In fact, the inoculation of both natural enemies is now used in many greenhouses where formerly only *E. formosa* was released. Initial populations of *T. vaporariorum* are usually higher in warm than in cold areas. Whitefly migration between crops occurs, necessitating higher densities of natural enemies, but for shorter growing seasons *E. formosa* does not control *B. tabaci* sufficiently in winter greenhouse crops. At present, a combination of the predatory mite, *Amblyseius swirski*, the predatory bug, *Nesidiocoris tenuis*, and the parasitoids, *Eretmocerus eremicus* and *E. mundus*, are applied to control *T. vaporariorum* and *B. tabaci* in greenhouse crops in warm regions.

Leafminers

Inoculative releases of *Diglyphus isaea* are done commercially for biological control of leafminers in greenhouse crops. In cold areas it is applied together with *Dacnusa sibirica*. In warm areas, natural populations of leafminer parasitoids are abundant year round and natural parasitism (up to 80%) controls leafminers for free. Further releases of *D. isaea* are made only when natural parasitism is low, especially when fine mesh screens are applied to the greenhouse.

Aphids

Suitable natural enemies are available to control all the aphid species that attack greenhouse crops, including the parasitoid *Aphidius colemani* and predators such as *Aphidoletes aphidimyza* and *Chrysoperla carnea*. Indeed, in warmer regions, in greenhouses not using broad-spectrum insecticides or fine mesh screens, aphids do

not normally reach economic thresholds, due to the presence of indigenous populations of their natural enemies.

Mites

Biological control of spider mites with *Phytoseiulus persimilis* on tomato crops has been largely ineffective and is not widely employed. However, a new species of predatory mite *Amblyseius swirski* and a new strain of *P. persimilis* (T strain) have produced better results in greenhouse tomatoes.

Caterpillars

Chrysodeixis chalcites, *Autographa gamma* and *Spodoptera littoralis* are kept well under control by *Bacillus thuringiensis* treatments. *Helicoverpa armigera* is also well controlled if the treatment is applied when eggs or young larvae are present. Inoculative releases of the parasitoid *Trichogramma evanescens* are also made for biological control of *C. chalcites* in some greenhouse crops.

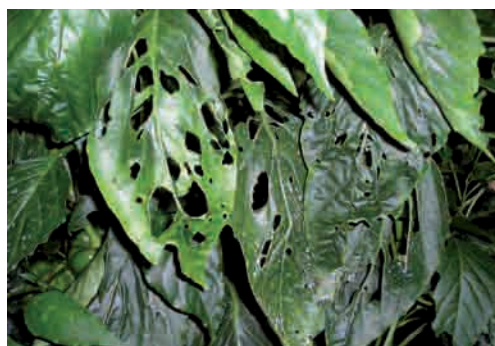


Plate 11

Damage to pepper leaves by the insect pest *Chrysodeixis chalcites* (Lepidoptera)

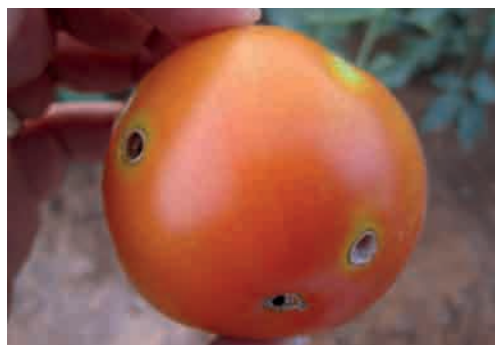


Plate 12

Damage to tomato fruit by the insect pest *Spodoptera littoralis* (Lepidoptera)

IPM AND BIOLOGICAL CONTROL OF INSECTS AND MITE PESTS IN GREENHOUSES

Developments in IPM in greenhouses have been unexpectedly rapid, and illustrate the great potential of alternatives to chemical methods. Climate management to improve the performance of natural enemies and decrease the development of pests and diseases is already part of greenhouse IPM programmes.

Biological control and chemical control

Most natural enemies are employed in IPM programmes; insecticides and natural enemies depend on the crop and country. The work of the International Organization for Biological Control of Noxious Animals and Plants (West Palaearctic Regional Section: IOBC/WPRS) Working Group, "Pesticides and Beneficial Arthropods", has been instrumental in selecting pesticides which least interfere with natural enemy activity. If selective insecticides are not available, alternatives, such as selective spraying, exist. For biological control to succeed, growers must be guided by producers and distributors of natural enemies, and by extension service personnel in the adequate integration of pesticides.

**Plate 13**

Bumblebees leave dark spots after pollinating a tomato flower, permitting the evaluation of the efficacy of pollination (flowers pollinated should be above 95% of flowers visited during all tomato flowering period)

There is every reason to believe that the rapid rise in the use of bumblebees for pollination in recent years encouraged the application of biological control, as large spectrum toxic pesticides could not be integrated with the use of bees.

Biological control and host-plant resistance

Tritrophic systems involving host plant, pest and natural enemies have been studied only recently. Such studies are essential for discovering the plant's role in supporting the action of natural enemies (whether combined with host-plant resistance or not), and how it might be manipulated to

the benefit of natural enemies. Particularly in systems where natural enemies alone are not sufficiently effective, it is important to improve the enemies' action through host-plant manipulation.

It is generally accepted that insect resistance in plants is compatible with biological control, but there are cases demonstrating the opposite. Breeding for insect resistance changes plant characteristics, affecting both herbivorous and entomophagous species. Only by understanding the biological processes between the different trophic levels is it possible to manipulate host-plant characteristics to maximize the combined control resulting from plant resistance and biological control.

BIOLOGICAL CONTROL OF DISEASES AND IPM

Until recently, IPM was limited to the control of insects and mites. In northern Europe, the Mediterranean region and the Near East, there are many disease problems, particularly in tomatoes, cucumbers and cut flowers. While some fungicides integrate well with the use of natural enemies, there are nevertheless increasing resistance-related problems. Furthermore, the limited number of biological control agents for diseases is a major concern.

Biological control of microbial plant pathogens

As with insect control, there are numerous problems in the chemical control of plant pathogens. Non-chemical control methods are sought because of pathogen resistance to fungicides and concern for the environment. Several diseases have developed resistance to a range of fungicides. In protected crops, resistance occurs mainly with *Botrytis cinerea* and powdery mildew fungi. Recently, with the increase in biological pest control, especially in protected crops, another disadvantage of fungicides has emerged: their side-effects on beneficial insects.

History of biological control of plant pathogens

Biological control of plant pathogens is a common phenomenon in nature and has been the subject of research for many years. As early as 1920, a number of reports highlighted the biological control of soil-borne diseases by antagonistic micro-organisms; it was understood that disease organisms became more abundant in sterilized soil than in soil with a resident micro-organism population or in sterilized soil with added antagonistic micro-organisms.

In recent years, there have been extensive studies of antagonistic micro-organisms against foliar and soil-borne diseases. Several successful antagonists have been isolated, but only a few are commercially available today for various reasons:

- Many diseases can still be effectively controlled by cheap and reliable fungicides and the disadvantages of fungicides – development of resistance, increasing developmental costs for new fungicides, and harmful effects on the environment, growers and non-target organisms – have only recently become more apparent.
- Both the pathogen and the biocontrol agent are more influenced by environmental conditions than in biological control.
- In many countries biological control agents of plant pathogens require registration before they can be used by growers, and the development of a commercial product costs more than for biological control of insects.

Mechanisms of biological control of plant pathogens

Biological control can be based on several different mechanisms, effective against different stages in the pathogen's life cycle.

Competition

New, young host surfaces are initially more or less sterile and can become colonized by both pathogenic and saprophytic micro-organisms. Rapid colonization of the surface by a saprophytic micro-organism may lead to depletion of the nutrients on the host surface. Fungal pathogen spores or pathogenic bacteria then arrive in an environment which is not conducive to their development. Inhibition of fungal pathogens in this situation can lead to a reduced rate of germination of pathogenic spores or to a reduced growth of germ tubes on the host surface. This leads to a reduction in the number of penetration points of the host surface and thereby to a reduction in symptoms such as the number of lesions. This is followed by a reduction of sporulation, which slows the spread of the disease.

Biological control based on competition is only effective against pathogens that use external nutrients during their pre-penetration phase (e.g. *Pythium*). This excludes all biotrophic fungal pathogens such as powdery mildews or rusts. In biological control based on competition, it is unlikely that resistance of the

pathogen will develop. It is important to ensure rapid colonization of the host tissue before arrival of the pathogen (for example in the case of *Bacillus subtilis*); once penetration has been established, the pathogen is no longer controlled by this mechanism and growth of the pathogen in the host tissue will take place at a normal rate.

Antibiosis

Plant pathogens can be biologically controlled through the production of antibiotic substances by the antagonist, inhibiting pathogen growth. Some fungal pathogens (e.g. *Fusarium*) are usually less susceptible to antibiotics than others. Antibiotics can be produced by both bacterial and fungal antagonists. Antibiotic-producing antagonists are found more often in soil than on above-ground plant parts. The antibiotics can be effective against both necrotrophic and biotrophic pathogens during several stages of their life cycle. Antibiotics will diffuse on the host surface, thereby making direct contact between the antagonist and the pathogen unnecessary. Two problems may occur in biological control based on antibiotic production: the pathogen may become resistant to the antibiotics (as with fungicides), and the antibiotics may be harmful to non-target organisms, including humans.

Hyperparasitism

Biological control based on hyperparasitism is a fairly common phenomenon in nature. In particular, powdery mildew fungi are often colonized by hyperparasites which feed directly on the plant pathogen. Biological control based on this mechanism does not require the biocontrol agent to be present before the pathogen arrives. On the contrary, since the hyperparasite usually needs the pathogenic fungus to feed on, this mechanism requires a certain level of infection by the pathogen before it can be effective. This is the main disadvantage of this mechanism of biological control: even low levels of infection may cause severe losses and therefore this method may not be attractive to growers. When the hyperparasite is applied, it needs to make direct contact with the pathogen to be effective, and distribution of the biocontrol agent over the host surface is important. The applicability of this method depends on the level of disease which can be tolerated without severe losses; therefore detailed knowledge of the relationship between yield loss and disease is needed.

Induced resistance

With induced resistance the host's defence mechanisms recognize and respond to the biocontrol agent as if it were a pathogen, and are then prepared for the real threat posed by the later arrival of the actual pathogen (for example induced resistance to plant viruses). It is somewhat similar to vaccination in animals. Stimulation of the host plant's defence must take place before the arrival of the pathogen; therefore the biocontrol agent has to be applied at an early stage of plant growth. In this mechanism, the biocontrol agent has no direct effect on

the pathogens; the effect only occurs through the host plant. This makes it more difficult to determine the effect of one biocontrol agent against a disease which can occur on various hosts, since the hosts may differ in their response.

Application of biological control agents

Application can aim at different modes of action and targets. Biological control agents can be applied on the aerial plant parts, in the soil, on seeds, on seedlings (e.g. on the roots), on harvested products and on crop residues. Practical manipulated biocontrol of leaf diseases is rarely applied, as there are few biological control agents registered against foliar diseases.

Soil application focuses on reduction of inoculum, whereas seed application primarily aims at reducing infection. Soil treatment can be achieved by adding spore suspensions of antagonists to unsterilized soils. To prevent soil fungi stasis, agents should be introduced into the soil with a quantity of nutrient, e.g. the food base on which they have been produced. Adding more spores to the soil serves no purpose. The competitive saprophytic ability of the biological control agents determines whether it will grow and spread through the soil after its application, or whether it will disappear gradually. Specific conditions favour the chances of the agents. For example, soil sterilization and pasteurization are excellent ways of preparing a good niche as they kill the plant pathogens, creating a biological vacuum which is quickly filled with new pathogen invasions. Pre-emptive inoculation with antagonists may prevent the rapid reappearance of the pathogens (suppressiveness of pathogens).

A widely used application of a biological control agent is root dipping of the nursery stock in a bacterial preparation of *B. subtilis*, which subsequently protects the plants against some soil pathogens.

An effective method of protection against seedling diseases (e.g. damping-off) is to cover the seeds with antagonists. Some of the antagonists will even establish in the rhizosphere assuring much longer protection. Since seed-coat organisms are the first to profit from seed exudates, they have a lead in the competition with pathogens (e.g. with *Trichoderma* spp.).

Current use of biological control of diseases in greenhouse crops

Biological control of soil and airborne pathogens is of increasing interest and biological agents have become available in the last 10 years for use in greenhouse crops. *Penicillium oxalicum* reduces the incidence of *F. oxysporum* f. sp. *Lycopersici*, in both hydroponic and soil systems, and *Trichoderma harzianum* and *Trichoderma koningii* control *Fusarium* root and crown rot.

Many of these biological control agents, however, are still being registered and are not yet commercially available in many countries.



Plate 14

Grey mould (Botrytis sp.) symptoms on a tomato stem

Future of biological control of plant pathogens

Biological control of plant pathogens will probably become more widespread in the next few years. However, it is unlikely that biological control will be able to completely control plant diseases and therefore it is important to research the possibilities for integrating biological control with other control measures. Integrated production and protection (IPP) means integration of biological control with chemical control, but also with alternative control measures, such as application of plant extracts and use of good agricultural practices (GAP).

In general, normal cultural practice aims primarily at optimum yields, using pesticides if necessary. With biological control of plant pathogens, cultural practices may need

modifying to influence the susceptibility of the crop, as well as the environmental conditions of the pathogen and biological control agent. For example, the yield of greenhouse-grown cucumber is higher when relative humidity is higher; this is why growers use a climate control setting to increase humidity in the greenhouse, but it also creates conditions conducive to *Botrytis* infection. The success of biological control is determined by the balance between the biological control agent and the target organism. If conditions greatly favour the target organism, biological control may not be sufficient, but a minor adjustment to the conditions can make the difference. Similarly, partially resistant cultivars used in combination with biological control offer better prospects than very susceptible cultivars. Other factors, such as the imbalances of the nutrient solution (excess of nitrogen or deficiency of calcium for example) may also influence a plant's susceptibility to certain diseases and pests.

Integration of biological controls and chemical control measures also offer potential as most biological control agents of plant diseases are not inhibited by insecticides. Some biological control agents are not affected by the fungicides used against their target pathogen or other pathogens; it is therefore possible to alternate the use of a biological control agent with a fungicide, depending on the circumstances. For example, if conditions favour the pathogen and not the biological control agent, a chemical is recommended; in other conditions, the biological control agent is recommended. For biological control agents incompatible with fungicides, it is possible to start with the biological control agent and only apply the chemical if disease gets out of control.

BIOLOGICAL NEMATODE, VIRUS AND WEED CONTROL

Biological control of nematodes

The development of nematodes can be inhibited in the soil: suppressive soils can have an antagonistic effect on plant pathogenic fungi, but they have also been discovered to contain a number of organisms with an antagonistic effect on nematodes. These organisms include nematophagous insects, predatory nematodes, fungi, protozoa and bacteria, but they are not yet available commercially for application in the biological control of nematodes. In order to stimulate the naturally occurring antagonists in the soil, detailed knowledge is needed of the soil's ecosystem and other environmental factors, such as humidity and temperature; likewise, for applying suppressive soils to diseased soil. Acquiring this knowledge is not simple, for example, it is difficult to make a realistic estimate of the number of dead or inactive nematodes in the soil. To date, nematophagous fungi are the most promising agents.

The nematicidal effects of the plant species *Tagetes patula* and *T. erecta* are well known. They secrete a product (an allelochemical) which suppresses populations of *Pratylenchus*, *Tylenchorhynchus* and *Rotylenchus* in roots and soils. In some countries, *Tagetes* spp. are used as catch crops; but they could be symptomless hosts of viruses (e.g. TYLCV, tomato yellow leaf curl virus) and therefore in warm regions their use is limited in greenhouse crops.

Biological control of viruses

There are two main approaches to biocontrol of virus diseases: biocontrol of vectors and biocontrol with attenuated strains. Vector biocontrol is essentially a form of biocontrol of insect pests and requires no further discussion. The use of attenuated strains is the only effective way of directly combating viruses (apart from the use of resistance).

Mild strains of viruses produce hardly any symptoms, and should not reduce production. Tomato mosaic virus (TMV) and pepino mosaic virus (PepMV) are examples of production constraints which have been overcome (TMV) or reduced (PepMV) by applying mild strains to the host before natural infection by the wild virus strain occurs. The presence of the mild strain prevents multiplication of the virulent strain, and thus keeps the crop healthy.

Protection by mild strains has led to a derived application (one of the best known examples of promising applications of biotechnology for increasing plant



Plate 15

Symptoms of the virus pepino mosaic virus (PepMV) in tomato fruits

resistance): transferring the genes for the viral coat protein to susceptible hosts makes them resistant to the corresponding pathogen. This method is a combination of biocontrol and resistance, since the cross-protection is transferred to the plant as a heritable character.

Biological control of weeds

In protected crops, especially in closed cultivation systems, biological control of insects is possible by using their natural enemies. In the case of weed control, this solution is not practicable. Biological weed control has been successful with non-native plant species which enter the country and become an uncontrolled plague. Following introduction of natural enemies (mostly insects) from the country of origin, the population decreases to an acceptable level. This classic method of biological control of weeds is known as the inoculative method.

Although not relevant to greenhouse crops, it is worth mentioning that biological control programmes of the invasive cactus species (*Opuntia stricta* and *O. dillenii*) have been implemented with great success during the last century in Australia (on 3 million ha) and South Africa (> 100 000 ha), using two exotic (from Latin America) phytophagous insects (the lepidopteran *Cactoblastis cactorum* and the mealy bug *Dactylopius opuntiae*). More recently (2012), FAO in collaboration with the Ministry of Agriculture of the Kingdom of Saudi Arabia, introduced from South Africa the exotic species *D. opuntiae* (var. *stricta*) for use in classical biological control of the invasive cactus *O. stricta* on over 50 000 ha of rangeland in southern Saudi Arabia.

PHYSICAL CONTROL

Control of pests and diseases by means of heat treatment or radiation is called physical control. Heat treatment is applied to control harmful organisms in soil and water; special equipment is sometimes used by growers to control weeds through flaming. Other methods are available to disinfect water.

Production systems where there has been incidence of root and stem diseases should be rigorously sanitized. All production houses benefit from passive solarization during the non-cropping period in summer: structures are sealed completely after wetting surfaces; temperatures > 50 °C are needed to assist in the eradication or at least the reduction of pathogens and other pests in the production area.

In order to start crops in soil free from pests and pathogens, chemical soil disinfection may be carried out – but cultural and physical methods, such as steam sterilization and solarization, should be adopted first when at all possible.

Sterilization of soil

Heat treatment of the soil is known as soil sterilization but this is not strictly correct, as even the most effective treatment does not eliminate all living organisms and the soil is not actually sterile after treatment. Partial sterilization or pasteurization are more accurate terms and are achieved through steam sterilization or solarization.

Solarization

Solarization is easily combined with other control methods to reduce the need for chemical control. Together with reduced dosages of chemical fumigants, it allows better management of soil-borne pathogens, which are otherwise difficult to control. Solarization followed by use of biocontrol agents has good potential, facilitating the introduction of antagonists, especially in warm regions.

Solarization is a form of soil pasteurization whereby solar energy is trapped beneath plastic sheets spread on the soil surface. It is a cheap and effective means of pasteurizing, and controls soil-borne pathogens, weeds and other pests. However, it is only effective when at least 30 days are available during a period of high solar radiation and can therefore only be applied in warmer climates, during the hot season, when no protected crop situation is present. The soil has to be wetted (water-holding capacity) to ensure that the absorbed energy goes beneath the top layer of the soil. A polyethylene cover prevents transpiration and escape of the heat into the air. Transparent plastic is more efficient at raising the temperature in the soil because of the greenhouse effect it provokes. The greenhouse effect is absent with opaque and black plastic. The depth of heat penetration (and hence the efficacy) is improved by prolonging the period of solarization. The temperature increase is about 10 °C in the topsoil and decreases with depth.

To control weeds effectively, a solarization period of 4–6 weeks (depending on radiation) is necessary. Annual weeds, especially Gramineae and parasitic weeds, seem to respond to this treatment; with perennial weed species, the results are not as good.

Soil solarization is a promising technique and may have an important future in many countries (especially with the phasing out of methyl bromide under the Montreal Protocol). Initially used only in hot regions during the summer, solarization is spreading to cooler areas and cooler seasons thanks to technological advances. Soil solarization controls numerous pathogens, including *Colletotrichum coccodes*, *F. oxysporum* f. sp. *lycopersici*, *V. dahliae*, *P. lycopersici* and



Plate 16

Application of soil solarization (soil disinfection from nematodes, pathogens, insects and weeds) during summer time, in tunnel greenhouses in the Jordan Valley

R. solani. Solarization also decreases the population of *Meloidogyne* spp., as well as many greenhouse crop insects which pupate in the soil (*Liriomyza* spp., *Tuta absoluta*, *Frankliniella occidentalis* etc.) in greenhouse crops. When used adequately, soil solarization decreases significantly the use of fumigants. Solarization of tomato stakes and hooks is a successful control method of some diseases such as *Didymella* stem canker, and could easily be achieved by storing this agricultural material in empty plastic greenhouses during the hot months of the year. In warmer areas, a significant kill of pathogens and insect and mite pests could be achieved simply by closing the greenhouse in the off-season (space solarization). Solarization of container media, such as peat, offers potential as it makes these products recyclable.

Unfortunately, only a limited number of countries, especially in warm regions, really take full advantage of this freely available natural control technique.

Agronomic benefits of soil solarization

In addition to eliminating certain pests, solarization also increases yields. Improvement in plant growth has been observed in solar-heated soils even when non-infested. One explanation for the increased growth is that upon soil sterilization (partial or complete), minerals are released and the nutritional status of the soil improves. Chemical and physical analyses of solar-heated soils confirm the presence of increased amounts of NO_3^- , NH_4^+ , Ca^{2+} , Mg^{2+} , K^+ and soluble organic matter. Another explanation for the increase in plant growth after solarization is the stimulation of beneficial micro-organisms: many saprophytes (notably heat-tolerant ones) survive better during solarization than most pathogens.

Steam treatment

Soil disinfestation using steam has been used by greenhouse growers for almost a century. Plant pathogens are eliminated by steaming and even seeds of weeds are annihilated (however, high expense means that it cannot be applied solely for weed control). Steaming the soil before planting also stimulates crop growth.

Heat treatment of the soil at 100 °C is the most effective method of soil sterilization. Bacterial and fungal pathogens, nematodes and even soil-borne viruses are killed at this temperature. A temperature of 70 °C maintained for half an hour, on the other hand, is sufficient for the control of fungal pathogens, bacterial pathogens and nematodes. Methods for soil steam treatment are: sheet steaming, drain steam system and negative pressure steaming.

Sheet steaming

Steam is blown under a sheet covering the soil and is left to penetrate the soil. The rate of success depends on the type, cultivation and moisture of the soil. To facilitate penetration, the soil should be dry and cultivated as deeply as possible before introducing the steam. This method works well in clay soils, but in sand

and loam soils the required temperature of 70 °C is reached only in the upper soil layers, and pathogens are able to survive in the deeper layers. Disinfestation of peat soils is generally very difficult owing to their water-retaining capacity.

Drain steam system

To improve the temperature range at greater depths, a new system was developed – drain pipes buried at a depth of 50–60 cm and 80 cm apart, through which the steam is blown. This system is permanent and expensive and, therefore, not widely adopted.

Negative pressure steaming

Negative pressure steaming is a new method: steam is introduced under the steaming sheet covering the soil, and pulled into the soil by negative pressure achieved by sucking air from the soil through buried perforated polypropene pipes by means of a fan. Negative pressure steaming is an important improvement on the traditional methods. It gives a similar or better temperature range compared with sheet steaming; it saves fuel and has lower investments compared with drain steaming. It can thus be concluded that the most efficient steam system for all types of soil is negative pressure steaming. For sustainable agriculture, steam sterilization of soil is preferable to disinfection by chemicals.

Disinfection methods for water

The development from soil to soilless cultures has not resulted in the disappearance of soil-borne diseases. Most root-infecting pathogens are also found in new cultivation systems. In a closed growing system involving recirculation of drain water, the risk of spreading root-infecting pathogens always exists. To minimize the spread of diseases, the drain water must run from the growing medium into the holding tank, where it is disinfected before reuse. Both surface and rainwater reservoirs may be contaminated with plant pathogenic fungi, bacteria and viruses; therefore, initially the whole water supply must be disinfected.

Heat treatment

Heat treatment gives effective control of fungal, bacterial and virus diseases. A temperature of 90 °C for 30 seconds is recommended. Heat exchangers provide efficient use of energy.

Oxidation

Oxidation by means of ozone or ultraviolet (UV) radiation are excellent methods for disinfesting water. Ozone is the most powerful oxidizing agent, inactivating human pathogenic viruses and bacteria. It is used to disinfect drinking water and industrial and municipal waste water; it reacts rapidly and has no residual power. As a donor of electrons (oxidation) to other substances, ozone itself is reduced to oxygen and may eliminate also fungi, bacteria and viruses.

Ultraviolet radiation, especially UV-rays with a short wavelength range of 200 to 280 nm, destroys micro-organisms by photochemical reaction.

Water filtration

Water filtration is used for selective disinfestation against *Phytophthora* spp. It has been used to purify drinking water for over a century. In tests for its efficacy against plant-pathogenic fungi, it proved unreliable against *Fusarium oxysporum* as the microconidia easily passed through the filter. Changing the flow rate or using different material could improve the efficacy.

Different ultrafiltration membranes with a pore size of 0.001 μm have been tested for total water disinfestation but, for various technical reasons, including blocking of the membrane, the method is not suited to greenhouses. Microfiltration membranes with a pore size of 0.5 μm could be used for selective disinfestation, preventing the spread of fungal spores and nematodes; however the same problems arise as with ultrafilters.

MECHANICAL CONTROL

Mechanical control of insect pests includes the use of exclusion insect nets, colour sticky bands and pheromone-baited water traps. Mechanical control concerns also weeds and diseases.

Using insect screens for mechanical exclusion of insect pests and vectors

Insects may enter the greenhouse from outside through the ventilation openings. Installation of screens on the ventilation openings will prevent or reduce the entry of pests. Screens with a mesh size of 0.15 mm exclude thrips; 0.35 mm keeps out whitefly and aphids; 0.8 mm is sufficient for leafminers. Screens do not suppress or eradicate pests, they merely exclude most of them; therefore, they must be installed prior to pest appearance, and supplementary pest control measures, such as intelligent chemical control and biocontrol, are required. Insect parasitoids and predators smaller than their prey can still immigrate through screens into the greenhouse; larger ones, unfortunately, cannot.

In the Mediterranean region, protecting crops from arthropods is considered more important than protecting them from the weather, so the physical exclusion of insects from the greenhouse should help reduce incidence of direct crop damage and insect-transmitted virus diseases. Theoretically, this exclusion can be achieved by fitting fabric screens with a mesh aperture smaller than the insect's body width over side and roof ventilation openings and doorways; in reality, some insect penetration persists.

It should be noted, however, that the use of screens might impede ventilation, resulting in overheating and increased humidity which promote plant stress and susceptibility to pests and diseases. Increased humidity necessitates more frequent

fungicide sprays than previously required in an unscreened greenhouse. Moreover, screens reduce light transmission; it is, therefore, necessary to make compromises in light, temperature and humidity management in order to avoid adverse effects on crops and their susceptibility to diseases. To minimize these harmful effects, it is possible to use forced ventilation, but this only helps to pull small insects through the screen. Thus, while screens can reduce immigrant populations of pests, they also reduce the immigration of beneficial arthropods. In neither case is exclusion total. The unfortunate fact is that the use of fine mesh screens when coupled with dusty conditions prevalent in warm regions seriously impedes greenhouse ventilation.

Types of screens

Various types of screen have been developed to protect crops from insects; the challenge for the grower is to match the type of screen to the local conditions (climate and insect populations).

Woven screens

Conventional woven screens are made from plain woven plastic. In commercial screens the slot is rectangular with a width smaller than the whitefly's body size – about 0.2 mm – but it must allow maximum air and light transmission. Screens designed to exclude *Bemisia tabaci* still permit a certain level of penetration, and they fail to exclude *Frankliniella occidentalis*. They do, however, exclude most larger insects, such as moths, beetles, leafminers, aphids and leafhoppers, and they retain bee pollinators inside the greenhouse.

Unwoven screens

These are made of porous, unwoven polyester and polypropylene or of clear, microporous, polyethylene fabric. All are very light materials which can be applied loosely and directly over transplants or seeded soil, without need for mechanical support. They have been used primarily in the open field as floating covers in early spring, to enhance earliness and to protect against early virus infection.



Plate 17

*Application of 50-mesh insect screen to greenhouse side ventilation as a mechanical barrier preventing the immigration of flying insect pests (leafminers, whiteflies, aphids, thrips, lepidopteran pests such as *Tuta absoluta*, *Chrysodeixis chalcites*, *Spodoptera* sp. *Helicoverpa* sp. etc.) into the greenhouse crop*



Plate 18

Dust accumulation on insect screens could impede greenhouse ventilation if not washed regularly

Note: Insect screens are a strong line of defence in an IPM programme when applied properly to all ventilation openings of the greenhouse.

UV-absorbing screens

These are claimed to protect crops from insect pests and from virus diseases vectored by insects, by modifying insect behaviour. Unfortunately, these effects are also extended to pollinators and natural enemies.

Whitefly exclusion

Whitefly-proof (50-mesh) woven screens are by far the most efficient mechanical barrier. The whitefly *Bemisia tabaci* is a small insect, about 0.2 mm wide, which transmits TYLCV (tomato yellow leaf curl virus) and has become the limiting factor in vegetable production in the Mediterranean region and the Near East. Its physical exclusion from greenhouses is crucial and, accordingly, whitefly-proof screens were developed. While the rate of whitefly exclusion is generally proportional to the screen's mesh, the insect's ability to pass through any barrier cannot be predicted solely on the basis of thoracic width and mesh size. There is an unexpectedly high rate of whitefly penetration due to the great variability in screen samples resulting from uneven and slipping weave.

Double door system or SAS

It is of paramount importance that all greenhouses be equipped with a double door or safety access system (SAS). An airlock SAS entrance into the nursery or greenhouse production area prevents the easy entry of insects into the main plant-growing areas. The SAS could also be fitted with traps and sticky yellow bands along both sides.

Mass trapping of insects

Colour sticky bands

Specific colours attract certain day-flying insects. For example, yellow sticky bands attract many insects and are often used to capture winged aphids, leafminers and adult whiteflies. Blue sticky bands are especially attractive to thrips.

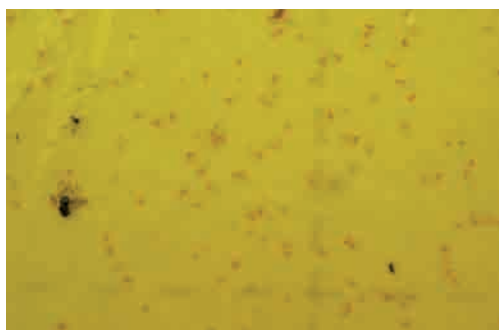


Plate 19

Yellow sticky bands for mass trapping (kill) of small flying insect pests (leafminers, whiteflies, aphids, thrips etc.)

Yellow and blue cards or bands coated with adhesives are, therefore, used to attract and capture small flying insects in greenhouses. For the purpose of mass trapping, sticky bands 10–40 cm wide are used for greenhouse crops (about 100 m/ha). The bands are installed at a height of about 1 m between greenhouse pools, 2 weeks prior to transplanting; they must be maintained throughout the crop cycle.

Yellow sticky bands are widely used in greenhouse crops. However, mass trapping is not recommended in greenhouses where

**Plate 20**

Numerous adult whiteflies attracted and killed by yellow sticky bands (other non-relevant small flying insects are also attracted and killed)

**Plate 21**

Large numbers of small flying insects are attracted and killed by yellow sticky bands

Note: Yellow sticky bands for mass trapping are not compatible with inoculative or inundative biological control as they attract and kill the released predators and parasitoids.

natural enemies are released for biological control as many flying beneficial insects will be attracted and killed by yellow sticky bands.

Pheromone-baited traps

Pheromone water traps are used successfully for the mass trapping of the new invasive species of lepidopteran, *Tuta absoluta*, in tomato greenhouses in the Mediterranean region and the Near East (2006–12). Since pheromone traps are so effective for catching male insects, numerous traps (over 10 per ha) placed throughout a greenhouse can sometimes remove sufficient insects to substantially reduce the local population and limit the ensuing damage. Nevertheless, the greenhouse must be fully equipped with insect screens to avoid attracting any additional males of *T. absoluta* from the environment outside the greenhouse.

Mechanical control of diseases

Many viruses and airborne fungi and bacteria spread within a crop from one or several sources, including crop plants, but also weeds occurring within or around a crop. By eliminating the source, an epidemic may be avoided. However, elimination of plants in the area surrounding a greenhouse is not simple when commercial crops are grown adjacent to private gardens, abandoned or desolated crop fields, or when virus reservoirs occur in the natural environment.

Removal (rouging) of infected plants in a crop is effective, particularly in young crops where a small number of plants form foci of infection for secondary spread. Any disease

**Plate 22**

*Light water traps baited with two pheromone lures for the mass trapping of adult males of *Tuta absoluta* in greenhouse tomato*

*Note: In case the traps are used in a greenhouse, the latter should be equipped with insect nets to prevent any attraction/migration of the pest *T. absoluta* from outside greenhouse surroundings into the crop.*

**Plate 23***Foci of viral infection with TYLCV*

Note: Infected plants should be removed as soon as symptoms appear to prevent whiteflies from visiting them and spreading more virus to the healthy plants.

development in the vicinity of the removed plant must be followed up. Rouging is particularly effective for viruses transmitted mechanically (e.g. pepino mosaic virus) or by vectors (e.g. TYLCV).

Dead leaves and flowers on a crop plant should be removed before they become a massive saprophytic base for inoculum. Pruning should always be done with a sharp knife, leaving no snags. Disease can often be avoided simply by reducing damage to roots, stems and foliage during cultural operations. Plants surviving from a previous crop (volunteers) form another

potential reservoir of infection within a new crop. Prevention is the best solution, adopting adequate harvesting techniques and soil cultivating practices.

Mechanical weed control

Elimination of weeds is important not only to remove the source of infections by insect and pathogens, but also to reduce competition with the crop for nutrients, light etc.

Flaming uses special equipment with propane or butane gas as fuel to produce high temperatures (800–1 000 °C). Flaming is done directly or indirectly, using equipment which produces infrared radiation. For application between crop rows, special protecting shields are required. Annual weeds only are killed; grasses have good tolerance and repeated treatments are necessary. Costs are high.

**Plate 24***Whiteflies on the underside of a weed (Malva sp.)*

Note: Failure to remove weeds from a greenhouse especially before planting the crop will allow the whiteflies to move from these weed sources to the new planted crop.

Black and white plastic mulch applied locally (on rows) or covering the total greenhouse ground is, nowadays, an important way of controlling weeds inside the greenhouse. Depending on the region and the season, total ground coverage may impact climatic conditions inside the greenhouse.

MONITORING

Monitoring involves systematically checking the greenhouse crop at regular intervals and critical times to gather information not only about the crop, pests and their natural enemies but also about diseases

and their antagonists. Visual observation of symptoms, laboratory analyses of soils or plant parts, weather data, sticky colour traps and pheromone traps can all be used to collect the maximum information necessary for an informed decision. The more often a crop is monitored, the more information a grower has about what is happening in the greenhouse.

Insect monitoring using colour sticky traps

For flying insects, yellow and blue sticky cards of various dimensions are recommended to monitor the population in greenhouses where biological control is and is not applied. A minimum of eight sticky cards (8 × 20 cm) per ha should be distributed to cover the various climate zones in the greenhouse (especially in non-climate-controlled greenhouses).

While coloured sticky bands are set at a fixed height and must be maintained throughout the crop cycle, sticky traps need monitoring and changing every week and their height must be adjusted to the top of the plant canopy. Sticky colour traps are undoubtedly excellent monitoring tools of small flying insect pests, but require a minimum of expertise for the recognition of captured insects species.

Insect monitoring using pheromone traps

Attractant-baited traps may be adopted for two major reasons. First, they are very sensitive and can capture pest insects present in densities too low to detect using other inspection methods. Second, traps baited with chemical attractants capture only one species or a narrow range of species, simplifying the identification and counting of target pests. This sensitivity and specificity make attractant-baited traps efficient, labour-saving tools compared with colour traps which are non-specific and require a specialist to carry out the monitoring.

Attractant-baited traps are used in monitoring programmes to:

- detect the presence of an insect pest;
- estimate the relative density of a pest population in a given greenhouse;
- indicate the first emergence or peak flight activity of a pest species, time an insecticide application or a biological control release, or signal the need for additional scouting; and
- carry out mass trapping of male adults.



Plate 25

The height of yellow sticky cards for monitoring of small flying insects (leafminers, whiteflies, aphids, thrips etc.) has to be adjusted as plants grow to obtain an accurate population estimate of these pests

**Plate 26**

Pheromone lure on a sticky paper card attracts specifically males of T. absoluta and allows the detection of the pest even when populations are still very low

Note: Pheromone traps are easy and reliable tools for the monitoring of certain lepidopteran pests in greenhouse crops.

The most common use of chemical attractants is in traps to monitor insect populations; although not all compounds used are pheromones, many publications refer to all attractant-baited traps as pheromone traps. For monitoring, chemical attractants are usually impregnated or encased in a rubber or plastic lure that slowly releases the active component(s) over a period of several days or weeks. Traps containing these lures are made from paper, plastic or other materials. Most traps use an adhesive-coated surface or a funnel-shaped entrance to capture the target insect. Traps for some pests are coated with an adhesive that also contains the chemical attractant.

Pheromones are difficult to apply in greenhouses: air currents in protected crops are different from those in the field, and as a result, male lepidopteran attraction to the traps could be negatively affected by active ventilation.

CHEMICAL CONTROL

Chemical control entails the application of botanical or synthetic, organic or inorganic compounds that have a killing, inhibiting or repulsive effect on organisms which are threatening to humans, animals and plants. Following years of application, the disadvantages of uncontrolled use of chemicals became apparent. A conflict developed between the social values of the public and the economic values of the chemical industry and agribusiness. There was a move towards alternative application methods and control strategies, and stricter demands were put in place for the approval of new chemical products.

Nevertheless, chemical control continues to play an important role in the control of pests and diseases in greenhouse crops. To combat the relatively small number of species of pests, diseases and weeds, a variety of chemical ingredients are used in a wide array of formulations. Pesticides are among the most effective instruments in crop protection: if used correctly they have a rapid and largely complete effect; they are applicable against nearly all pests and may be used even at a late stage of development with many pest populations.

Chemicals are important in protected cultivation – even more important than in other cultivation methods given the high value of the crops grown (in particular ornamental crops). The zero-tolerance of pests in the export of ornamentals and the non-acceptance of cosmetic damage in certain crops contribute to a higher

usage of chemicals in protected crops. Given the high value of protected crops, expensive chemicals and costly methods of application (such as soil drenching) may still be economically justified in order to achieve the required high standards of pest and disease control. Moreover, greenhouse cultivation changes the circumstances under which crops are grown more than any other type of cultivation – the enclosed environment and intensive monoculture encourage the development of pests and diseases, making chemical control necessary.

Application of pesticides

Pesticides can be applied as a preventive treatment to protect crops, or as a curative treatment to destroy or limit population development of noxious organisms.

Uptake and transport of the chemical through the plant is a systemic mode of action, where the protective effect is felt also by plant parts which do not receive direct treatment. In the case of fungicides, systemic chemicals can reach the already-existing infections in the plant and eliminate them, providing curative protection. Non-systemic fungicides (so-called contact pesticides) only have a superficial effect, and their role is mostly preventive.

Pesticides can be applied to the leaf, stem, root or seed-coat. Most products, however, have been developed for application on aerial plant parts. Special pesticide formulations have been developed for the various application methods. When selecting the appropriate application technique for a certain pest or disease, a range of considerations are necessary:

- product to be used
- equipment available
- type, stage, location and spread of the target organism
- kind of crop and its stage of development
- susceptibility of the crop, or pest or disease to the product
- weather conditions
- cost

The application of sprays, dusts and mists is labour-intensive, but they also leave a residue on the plant that continues to kill after application. As greenhouses are enclosed, it is also possible to use smokes, fogs and aerosols. These methods propel fine droplets or particles of the pesticide into the air, so that insects and other organisms within the crop are also reached. Greenhouse application can be through a crop treatment or a space treatment; products can be applied in dry or liquid form.

Dry products

Dry chemical products can be applied in dust form or as granules; they have the advantage that they can be used in situations where water is a limiting factor. In

some countries, dustable powders can only be used in greenhouses, as the product may be sensitive to wind and thermal changes; however, dusting is not a common method of pest control, due to the visible residue on the plants. Granules are added to the soil just before or during sowing, and mixed with it afterwards; the active ingredient dissolves into the soil moisture. These products can provide control of insects and nematodes.

Similar to granules is the fast developing technology of seed-coating. Seeds are intensively mixed with a powder or a liquid to which the pesticide has been added. If a sticky additive is included, less pesticide is required, and a pigment is also usually added to distinguish treated seeds. The result is a smooth, solid, soluble coating around the seed which can protect the young seedling in the soil against, for example, insects and fungi.

Liquid products

Liquid chemical products can, if required, be diluted with water, and a variety of apparatus exist for their application. Penetration through the crop and product coverage on the plant and the crop must be taken into account when determining the amount of spray solution required and the droplet size. Depending on the type of product, 100 percent coverage is not always necessary: a systemic pesticide does not need to cover the complete crop, but complete coverage is necessary when a contact pesticide (most oils and solvents) is used to kill a relatively immobile insect. To achieve a satisfactory degree of coverage, the distribution of the droplets, i.e. the droplet size, is very important, while the amount of sprayed liquid is less relevant.

With low volume techniques, both crop-oriented and space treatments can be given in the greenhouse. Space treatment is the application of a pesticide through the air so that it spreads homogeneously in space and falls very slowly onto the crop. Advantages of space treatment are that less time is required and the crop stays dry (but not all agents can be applied in this way). On the other hand, the crop effect tends to be weak, which means that mainly flying insects are reached. If used against fungi, this method only works preventively and when there is little damage. To improve the efficacy of this technique, ventilation openings should be closed, but the temperature and RH (relative humidity) should not be allowed to rise too high to avoid damage to the crop (the RH cannot be too low either). The condensation water inside the greenhouse will contain chemical residues and should be collected.

Chemigation

When growing a crop in soil or on an artificial medium in greenhouses, chemicals can be applied through the irrigation system, which reduces not only costs but also workers' and beneficial insects' (natural enemies and bees) exposure to toxic pesticides. Various pesticides can be applied this way, including fungicides,

insecticides and nematicides. A pesticide should be applied gradually during the period required for complete circulation. It should be remembered that the pesticide will only be active in the solution for a limited period, depending on the chemical used.

Guided or supervised control

While IPM involves several alternative control methods, guided control only deals with chemical control. Guided control aims to reduce pesticide use by determining whether a control for a certain pest is necessary and, if so, when it should be applied (for optimum effect). In guided control, chemical control is only deemed necessary when the economic benefits counterbalance the costs; it implies use of curative rather than preventive pesticides. In both IPM and guided control, complete eradication of the pest or disease should not be pursued: it may not be required to minimize the loss, it might be economically or technically impossible, and it could be undesirable because of unacceptable side-effects. The rules of guided control are also adopted in integrated control, but not the other way round: what is important in IPM is not necessarily important in guided control.

In order to decide whether to spray or not, a grower needs to be able to recognize the pest insects and diseases of his crop. During the growing season, the crop must be observed and noxious organisms monitored: the level of infestation is extrapolated to the end of the season, when the harvest takes place and the yield loss is known. Forecasting the expected damage and loss is not always accepted practice – it is preferable to “play safe”, especially when dealing with high-value crops, and growers do not usually follow the guided control principles. When monitoring a noxious organism, it is necessary not only to count the numbers, but also to observe the stage of development of both crop and pest. For example, the caterpillar stage of a pest insect can be dangerous for the crop, and the adult stage not. Moreover, one development phase may be easily controlled, while another poses more problems. The damage threshold level is not a constant factor throughout the growing season, as the damage caused by the pest or disease also depends on the crop stage. For example, a pest can cause enormous damage and yield loss during germination, while a later infestation will give no reduction in yield at all. Tomato leafminers (e.g. *Liriomyza* spp. and *Tuta absoluta*) are more injurious to the tomato crop in its early stage of development than when the plant canopy is fully developed. Therefore, and contrary to common belief, pest thresholds are dynamic and should be linked to the plant growth stage.

The damage threshold may also be influenced by the environmental conditions. Moreover, if a single spraying can reduce several pest populations at the same time, it could be decided to apply controls at a lower damage threshold level than for only one pest population. The damage threshold is lower, because combined control makes the intervention cheaper: the balance between control costs and loss through damage is reached at a lower damage level, i.e. a smaller pest population.

Guided control requires technical expertise and is not yet implemented everywhere. Calendar spraying continues to be widely used for a variety of reasons:

- Growers may lack the necessary information about the damage threshold of the noxious organism.
- Growers do not always have the relative knowledge about pest organisms and the mode of action of the chemical product.
- Proper observation and sampling techniques are not always available, especially for fungi.
- Observation time is viewed as an extra labour cost (even though the total costs will in reality be reduced).
- In some cases (e.g. with ornamentals, especially pot plants), damage thresholds are very low (but not always zero), which encourages growers to spray for completely “clean” products.

Side-effects on beneficial organisms

Pesticides can exhibit primary or secondary effects on bees, predators, parasitoids and pathogens of target pests. Primary effects are direct or indirect, depending on their exposure and on the biological parameter influenced. Direct mortality of beneficial organisms may be caused by the following:

- direct contact during application
- pesticide residues
- taking up contaminated prey
- intoxication by fumigants
- contact or contamination with soil disinfectants

Secondary effects include the following:

- killing the prey/host of a beneficial organism
- killing species which produce alternative food (e.g. honeydew)
- taking up contaminated food
- directly stimulating the pest (e.g. some pyrethroids enhance reproduction in *Tetranychus urticae*)

Fungicides directly affect entomopathogenic fungal biocontrol agents by inhibiting spore germination and vegetative development (mycelial growth); they also reduce the viability of conidia and their survival and activity on plant surfaces. Generally, herbicides, acaricides and fungicides have less effect than insecticides, although mycopesticides are highly susceptible to fungicides.

Effects on predators

Most pyrethroids and carbamates are harmful to predatory mites. *Aphidoletes aphidimyza* is susceptible to insecticide and acaricide treatments, and is also affected by organophosphates. Coccinellids have a high mortality rate as a result of nearly all compound groups, except micro-organisms and soap. Chrysopids are not harmed by acaricides, most pyrethroids, soap or micro-organisms, but they are affected by the majority of insect growth regulators (IGRs) and organophosphate. Predatory bugs are harmed by pyrethroids, carbamates, most organophosphates and some IGRs. Fungicides and herbicides are relatively harmless for coccinellids, chrysopids and predatory bugs, but partly harmful to predatory mites.

Effects on parasitoids

Synthetic pyrethroids and pyrethrin are very harmful to adults, regardless of the species. Organophosphates are very harmful to unprotected stages and, with a few exceptions, also to the protected life stages of the parasitoid. IGRs and most of the acaricides are harmless to both the susceptible and the protected developmental stage of the parasitoids. Plant extracts (except pyrethrin and neem extracts), soap and micro-organisms are harmless. Fungicides are generally harmful to adult parasitoids. Very few herbicides are harmful to adult wasps, but not to wasps in other developmental stages.

Pesticide resistance

Pests and pathogens can overcome the toxic effects of pesticides by metabolizing the active ingredient into less toxic components and reducing the absorption of the chemical (physiological resistance) or by avoiding exposure (behavioural resistance). No doubt, pest and disease resistance development will continue to be the biggest challenge to chemical control.

In greenhouses, pesticide-resistant strains of fungi and pests appear frequently. This phenomenon occurs because the greenhouse is a closed system in which the population of selected strains is not diluted by the outdoor wild population. Moreover, the optimal conditions for their development prevail for long periods in greenhouses, and the number of generations, therefore, increases; to maintain control, frequent pesticide applications are necessary. As a result, selection pressure towards resistance to pesticides in greenhouse crops is significantly higher than in open field crops.

Fungicide resistance

The main pathogens known to develop resistance to fungicides in greenhouses are *Botrytis cinerea* (grey mould), *Pseudoperonospora cubensis* (downy mildew of cucurbits), *Didymelia bryoniae* (gummy stem blight of cucurbits) and *Sphaerotheca fusca* (powdery mildew of cucurbits).

The benzimidazole fungicides (benomyl, carbendazim, thiophanates) have high resistance potential against pathogens because they have a specific mode of action. Resistance is not usually associated with a significant loss of fitness of the pathogen. It occurs in populations of *B. cinerea*, *D. bryoniae*, *Fusarium* and powdery mildews. Mixtures and alternations with multi-site contact fungicides may delay this selection before resistance becomes widespread. Acute problems of resistance to dicarboximide fungicides (e.g. iprodione, procymidone, vinclozolin) arise when fungicides are used intensively and exclusively over many seasons. Isolates are moderately resistant and tend to be almost as fit as sensitive strains in the absence of fungicides. It is recommended to restrict the number of dicarboximide treatments to no more than three per crop in greenhouses, whether resistance exists or not. When infection pressure is high, it is usually recommended to alternate or mix these fungicides with protectants, such as chlorothalonil or captan, or with biocontrol, where there is usually no selection for resistance.

Ergosterol biosynthesis inhibitors (EBIs) are a group of fungicides, including triazole, imidazole and pyrimidine. In contrast to the strong sharp resistance towards benzimidazoles and dicarboximides, resistance towards EBIs develops in the form of slow shifts in the pathogen population. For example, powdery mildews in greenhouses were controlled for several years by benzimidazoles, hydroxypyrimidines, pyrazophos and EBIs. There is resistance in populations of *S. Fusca*, but the alternation of fungicides practised in many countries is helping to solve the problem. It is generally recommended to rotate or mix EBI fungicides with fungicides from other groups as well as with biocontrol.

The failure of disease control in greenhouses is exemplified by the history of grey mould epidemics. Multiple resistant isolates occur in greenhouses with resistance towards benzimidazole, diethofencarb, dicarboximides and ergosterol biosynthesis inhibitors, and even extreme summer conditions do not prevent the survival of fungicide-resistant isolates.

Phenylamide fungicides that inhibit RNA (ribonucleic acid) synthesis were introduced in the late 1970s for Phycomycetes control, at a time when *P. cubensis* was controlled mainly with protective applications of dithiocarbamates and chlorothalonil. In the early 1980s, phenylamide metalaxyl was released and soon afterwards resistant strains were selected. Metalaxyl-resistant strains seem to be more competitive than wild-type strains. Resistance was found also in *Phytophthora infestans* on tomato. Anti-resistance mixtures of metalaxyl with protectant fungicides were developed to cope with phenylamide resistance.

Insecticide and acaricide resistance

Insecticide and acaricide resistance of nearly all important arthropod greenhouse pests is well documented. Besides genetic and operational factors influencing the selection of resistant individuals, biotic reasons (e.g. generation turnover, number

of offspring per generation and type of reproduction) have a major impact on resistance development. Most of the pest species in greenhouse crops are prone to resistance selection with regard to these biological parameters.

Bemisia tabaci has recently developed resistance against a range of conventional insecticides (neocotinoids and pyrethroids) as well as against IGRs and juvenile hormone analogues (Pyriproxyfen and Buprofezine). *Myzus persicae* and *Aphis gossypii* have developed resistance to the most commonly used synthetic pyrethroids in greenhouse crops, while *Frankliniella occidentalis* has developed resistance against most pesticide groups, resulting in severe economic losses in the affected crops.

Resistance management

In order to reduce the pressure on the development of resistance in pathogen populations, it is usually better to limit a pathogen's exposure to a group of fungicides. The number of applications of fungicides with the same mode of action must be limited, especially when fungi have many cycles during the growing season. Moreover, the application of non-chemical methods is also recommended.

Insecticide resistance management strategies for pests comprise different approaches classified as: management by moderation (low dosages, reduced number of applications), and management by multiple attack (application of mixtures). For IPM programmes, non-target effects on natural enemies have to be considered.

Attempts have been made to improve the compatibility of beneficial organisms with pesticide application by selecting beneficials with resistance to chemical pesticides, but this is often a cumbersome procedure as the pesticides used may change often. The degree of resistance, stability and possible influence on the fitness of the tolerant organisms must all be assessed before the selected organisms can be used in pest or disease control.

In addition to its compatibility with other control methods, resistance management is another important aspect of chemical control in IPM. Resistance management involves various strategies for minimizing the risk of development of resistance to pesticides in the target pest.

For situations of reliance on chemical control, several strategies of resistance management have been developed, categorized as follows:

- Moderation refers to the application of pesticides at lower rates, lower frequencies and less thoroughly, and aims at delaying or forestalling resistance by allowing a portion of the susceptible individuals to survive.
- Saturation aims to prevent the evolution of resistance by rendering resistance genes functionally recessive, through exposure to dosages that are lethal to

heterozygous-resistant individuals. This can be accomplished in certain cases without increasing the dosage rate of insecticides per unit area, for example, through addition of an attractant to the insecticide (e.g. pheromones).

- Multiple attack involves the use of two (or more) pesticides in rotation or in combination. This strategy requires the availability of pairs of pesticides with non-overlapping, cross-resistance spectra. It takes advantage of the initially rare frequency of genes for resistance to new types of pesticides, possible interactive effects between pesticides (synergism, negative cross-resistance), and low fitness in resistant phenotypes.

PRACTICAL RATIONAL CHEMICAL CONTROL OF GREENHOUSE PESTS AND DISEASES

A range of tactics and schemes are available for the management of insects and diseases, including prevention and sanitation (discussed above). The use of pesticides will remain, at least in the short to medium term, an important strategy, allowing the grower to continue to produce economically a quality crop.

It is essential that the use of chemicals in IPM be based on informed decisions (ET – economic threshold) and only after considering the impact of the factors regulating the populations of pests and pathogens, making sure that there are no other effective management tools. Even though a degree of chemical control might still be necessary, pesticide use and associated risks must be observed. In this case, IPM is foreseen as a way to keep pesticide applications to the minimum required and at the lowest effective dose with the most selective products, while observing the necessary safety intervals before harvest.

Five major steps are recommended when using pesticides to maximize the success of the operation; they are outlined below.

Step 1: Proper identification and risk assessment of the pest's and disease's life stage

The first most crucial step is correct identification of the pest or disease causing the problem. Proper identification is mandatory and false identification leads to possible misunderstanding of the pest's or disease's behaviour and of the potential dangers. Correct identification allows the grower to understand the pest or disease, seek out additional specific information about potential dangers to the crop, and know how to best manage it.

Populations of pests and diseases must be monitored regularly following scientifically established methods appropriate to the region or locality. Existing and validated forecasting models for diseases should be implemented and adequate insect monitoring tools should be used depending on availability. Proper identification and risk assessment is the first and primary step in managing pests and diseases. Solving Step 1 leads to Step 2.

Step 2: Choosing the proper pesticide

Only after the grower has properly identified the pest or disease can the best pesticide be selected. Pesticides are sometimes effective against one pest or disease but useless against other closely related ones. Also, one pesticide may be effective against a specific developmental stage while another may be effective against a different or perhaps all developmental stages. Correctly identifying the pest or disease and understanding its biology and life cycle allows the grower to choose the best pesticide. Growers should consult extension agents or pesticide companies and dealers for more advice.

Step 3: Proper usage of pesticides

After selecting the pesticide, growers must decide on the amount to use. The information is contained on the label, but more than one option is usually given. To make the correct choice, as much knowledge as possible about the biology of the pest or disease must be gathered. Factors, such as pest size and population, play an important role in insect management. For example, small worms may require the lowest recommended label rate while large worms may require the highest label rate; however, continuous use of the higher rate can lead to insect resistance. Once a pest or pathogen population becomes resistant, it is difficult for any amount of that pesticide to control it. Continuous overdosing with one pesticide can cause resistance to develop not only to the pesticide applied, but perhaps to other pesticides as well. Workers must have the proper measuring devices to make sure that the correct amounts of insecticide are used.

Greenhouse growers frequently have smaller areas to spray than growers in the field and therefore need smaller amounts of pesticides. For example, a field tomato farmer may use 1 000 cc/ha of a material in 500 litres of water; this is an easy quantity to measure. However, in a greenhouse, only 20 litres of spray may be needed to do the greenhouse block; this means that very small amounts (even less than 1 teaspoon) must be measured, but a spoon is a non-graduated container and is a very poor, inaccurate and dangerous way to measure pesticides.

Growers should therefore buy a set of graduated cylinders marked in millilitres and a set of good quality measuring cups. Glass can be used, but plastic is often preferred to avoid breakage. Measuring devices, such as graduated cylinders, have pouring lips and graduated measuring markings that allow for accurate measurement and preparation of spray in quantities from 1 to 500 litres or more. Measuring devices can guarantee accurate measurement, thus allowing for effective kill, a safe range of pesticide residues on the crop, more efficient use of chemicals and money, and the reduction or elimination of phytotoxicity. Proper measuring devices also play an important role in the overall safety and handling of pesticides: they help prevent spillage of concentrated materials. Pesticide concentrates are usually handled when the sprayer is loaded and dilute sprays are being prepared, and special handling precautions are necessary at this time. The applicator must

be particularly careful when handling finished sprays but even more so when dealing with concentrated material. Workers must be mindful, cautious and use all pesticides according to the label.

If excessive quantities of pesticide are used, the following problems can arise:

- The crop can have more residue than the law allows, posing health hazards to consumers and potentially preventing the crop from entering the market.
- The crop can be confiscated by authorities for excessive residues and destroyed without any compensation to the grower.
- Resulting publicity can harm future markets for that commodity.
- Re-entry by workers into overdosed areas is potentially dangerous and can lead to illness, medical costs and liability to the grower.
- Overdoses can speed up the pest's or pathogen's resistance process.
- Production costs increase without the benefit of added profits.
- Phytotoxicity is more likely to occur.

It is important not to exceed the label rates. If the maximum labelled rate does not achieve the desired results, other reasons for failure must be sought. It is unlikely that additional amounts of the same material will improve the situation. The old cliché – “If a little is good, a lot is better” – can have disastrous results.

Step 4: Proper timing

The chosen pesticide should be applied at the correct time and this is not an easy task. Determining the best time to apply chemical control is a dynamic and comprehensive process, and failure to treat at or near the correct time is one of the major reasons for unsuccessful pest and disease management. Despite the difficulties involved, steps may be taken to help make a reasonable decision:

- Regularly and thoroughly inspect the crop, noting the presence of pests and diseases and any increase in incidence.
- Know the pest or disease, its behaviour, and its ability to damage the crop.
- Be aware of economic thresholds if available.
- Know the biology of the pest or disease so that pesticide application can be aimed at the weakest, most vulnerable stage. Some stages of insects and mites, such as the egg stage, can seldom be controlled. Young larval or nymphal stages are more easily controlled and require less insecticide than older stages. Pupal stages are generally not affected by insecticides (large larvae nearing this stage are also difficult to control). Once populations reach high numbers, even if 95 percent are controlled, the remaining 5 percent can still be a significant number.

Further considerations must be made with regard to timing of greenhouse insect control, in particular:

- Mites and whiteflies should be controlled as soon as they are observed. Growers should not allow populations to reach high numbers. Sprays for mites and whiteflies should be spaced at no longer than 4–5-day intervals until control is achieved.
- Worms and caterpillars should be controlled when 14 days old.
- It is generally best to apply insecticides in the late afternoon or evening hours when temperatures start to fall. This also allows for maximum exposure time before the sprayed area is aired for employees; also, many insects are most active at night. The risk of phytotoxicity (burning) is greater when applications are made during the middle of the day. On the other hand, it has been reported that better mite control can be obtained by spraying early in the morning hours. As a rule, insecticide or miticide applications should be made while temperatures are low. A spray application time should be chosen when control, phytotoxicity, irrigation, temperature and worker re-entry considerations best fit the overall operation.
- Insecticides should not be applied when plants are water stressed. Water-deficient plants are more subject to phytotoxicity damage.

Step 5: Proper application of pesticides

Proper application, like proper timing, is one of the most important steps in pest and disease control efforts. It does little good to complete the first four steps properly and then fail to deliver the material to the target area. There are numerous factors to be taken into account and various spray methods to consider for proper application of pesticides.

Spray equipment must be properly calibrated. A calibration error can quickly result in under-dosing (not obtaining control) or overdosing (illegal and harmful). Application of the proper amount of material is closely related to calibration.

Growers should purchase the specific equipment for the operation and the target pest or disease. Each pest and disease differs in habits and behaviour and one piece of equipment may not meet all needs. For example, tests involving equipment to control greenhouse mites varied widely in results. High volume sprayers provided 59% control, rotary atomizers 67%, and pulse jet applicators 8%.

High volume sprayers have been used for years in greenhouses. They are popular, can accommodate a wide range of pesticide types, and offer flexibility in the operation. However, high volume sprayers require a great deal of labour, are time-consuming to use, and are considered low in application efficiency. It has been estimated that less than 10 percent of the active ingredient reaches the actual target using high volume systems. However, most pesticides are labelled for high volume application. As previously discussed, most greenhouse insects and mites

are found on the underside of the leaves making it difficult for the spray to reach the pest, especially for some insecticides with physical modes of action (such as soaps and oils).

There has been extensive research into low volume methods of pesticide application in greenhouses: aerosol generators, foggers, rotary atomizers, electrostatic applicators, mist blowers and pulse jet applicators should be considered by growers. The drawback is that some low volume systems require special formulations and specific accessory equipment. Low volume equipment may use as much active ingredient per hectare as high volume units, but they use less carrier to apply the material. Low volume systems can be efficient in delivering pesticides as they include contact, fumigant or residual control, but their greatest advantage is the time saved.

Each piece of equipment, whether high or low volume, has an advantage for a particular job. There is no perfect piece of equipment, so growers need to look carefully at all available options. It should be noted that it is illegal to use some low volume spray equipment to apply pesticides in greenhouses.

For the best results, knowledge of the pest or disease and its biology should be combined with the equipment's specific capabilities. To reach the underside of the leaves in thick canopy crops, a driving, directed spray may be required; if the canopy crop is thin, a rolling fog, atomizer or electrostatic applicator may be appropriate. Many pesticides produce vapours that help control pests and pathogens, even when coverage is less than desired; nevertheless, proper coverage can enhance the fumigating properties of a pesticide.

Some insecticides also encourage insects to move into those areas where they come into contact with the insecticides. Some new materials can translocate from the top of the leaf to the bottom, improving efficiency and compensating for the constraint of equipment that delivers spray best to the topside of the leaf. Even though greenhouse spray equipment is far from ideal, the most serious problem facing greenhouse vegetable growers remains the lack of registered, effective pesticides.

For correct application of pesticides, proper maintenance of spray equipment and its numerous parts is essential. Many spray operations are hampered and effectiveness drastically reduced because the spray cannot be delivered at the proper pressure, droplet size or pattern due to excessive wear, improper adjustment, or broken or improperly working parts. Growers should regularly check nozzles and discs for wear and tear (greater when suspensions and wettable powder formulations are used) and replace them when they do not meet specifications. Workers need to understand spray pressure and have accurate gauges, as even minor inaccuracies can result in improper droplet size and failure

to deliver the desired coverage. Moreover, most pesticides are highly corrosive and react with hoses, lines, nozzles, tanks and other components, affecting the spray patterns and leading to the formation of foreign particles that clog the equipment. Therefore sanitation is important:

- Spray should be used as soon as it is mixed, and the equipment thoroughly cleaned and rinsed immediately after spraying.
- Workers must mix only sufficient spray for the job. Leftover spray can quickly destroy the sprayer, sprayer parts, lines and components. However, it must be carefully and legally disposed of if not used on the crop, as disposal of pesticides is an increasing environmental concern. Growers must plan carefully their requirements, use what is mixed, and clean up properly afterwards.
- Spray equipment must be properly stored after cleaning to keep it free of dust, dirt and other foreign materials (e.g. pieces of rubber lines) that may enter the system, blocking it and causing poor spray patterns, particularly when pressure is applied.
- Water is the most commonly used diluent (carrier) for pesticide sprays and it must be clean and free from contaminants. Water for the spray tank may contain dirt, sand or corrosion from the pipes or lines, or loading hoses and pipes can be dirty, causing severe problems to operations. Growers should filter water as many times as possible: between the source of water, the spray tank and where the water enters the tank; also between the tank and the final nozzle, so that the spray can flow and be delivered in the pattern according to equipment specifications.

If a spray job needs repeating because of inaccurate pest or disease identification, or poor application or timing methods, potential profits can be reduced and the crop can be vulnerable to pests and diseases. Of all the factors and measures necessary for pest and disease control, none are more important than the overall proper delivery methods.

Pesticides should be used as soon as they are mixed. Once mixed with water, the pesticide begins to change and its effective life can be only hours. Water with a pH of over 7.0 can be particularly detrimental to many pesticides; generally speaking, the higher the pH, the faster the pesticide is broken down and rendered useless. Under conditions where the underground water is frequently high in calcium carbonate (pH 8.0–8.5), it is even more important to not allow finished spray to stand longer than necessary.

Storage of pesticides

Only fresh pesticides should be used. Growers should try to purchase the quantity required and not plan to store materials for longer than a single season. Pesticides should not be left on the shelf longer than is necessary.

**Plate 27**

Safe locked storage system of pesticides, made from iron and well ventilated

Note: No pesticides should be laid directly on the ground.

**Plate 28**

Model of signalled panel displayed on the wall of pesticide storage (hazards)

Pesticides must be stored in a safe, dry location. The best storage temperatures are generally room temperature (20–30 °C); temperatures over 40 °C are not recommended. Certain pesticides undergo undesirable changes if the storage temperature drops below freezing. Applicators must follow the label instructions for specific storage information. Applicators must follow local government laws with regard to storage sheds, locks and warning signs.

Safety issues

Pesticides can create serious problems when common sense and rules of safe use and handling are not used. The pesticide label is considered a legal document: “the label is the law”. It is the duty and legal responsibility of the user to read and understand all the directions and information on the label, and to seek interpretation of any unclear part. Pesticide dealers, manufacturers and their representatives, as well as the extension service can aid in interpreting pesticide labels. Lack of understanding of the label or misuse of a pesticide can have serious consequences. The label contains information on the safe use of its contents, protective clothing, worker contact, poisoning symptoms, disposal and other

information. The user is encouraged to become familiar with all safety and other aspects of the label before use.

CONCLUSIONS AND GAP RECOMMENDATIONS

Numerous GAP codes, standards and regulations have been developed in recent years by the food industry and producers’ organizations and also by governments and NGOs, aiming to codify agricultural practices at farm level for a range of commodities. Their purpose varies from fulfillment of trade and government regulatory requirements (in particular with regard to food safety and quality), to more specific requirements of specialty or niche markets. The objectives of these GAP codes, standards and regulations include, to a varying degree:

- ensuring safety and quality in the food chain;
- capturing new market advantages by modifying supply chain governance;

- improving use of natural resources, workers' health and working conditions; and
- creating new market opportunities for farmers and exporters in developing countries.

Good agricultural practices are “practices that address environmental, economic and social sustainability for on-farm processes, and result in safe and quality food and non-food agricultural products”. The four pillars of GAP (economic viability, environmental sustainability, social acceptability and food safety and quality) are included in most private and public sector standards, but the scope which they actually cover varies widely. The concept of GAP may serve as a reference tool for deciding, at each step in the production process, on practices and outcomes that are environmentally sustainable and socially acceptable. The implementation of GAP should therefore contribute to sustainable agriculture.

In line with these GAP standards, maintaining a healthy greenhouse crop is more than essential for an economic and sustainable greenhouse vegetable and ornamental production. This requires first consistent monitoring, which involves systematically checking the greenhouse crop at regular intervals and at critical times to gather information about the crop, pests and their natural enemies, diseases and their antagonists. Visual observation of symptoms, laboratory analyses of soils or plant parts, weather data, sticky colour traps and pheromone traps, are some of the available tools which should be used to collect the maximum information necessary for an informed decision to make sure there is a clear distinction between non-parasitic afflictions (plant stress and other physiological disorders) and those caused by pests and pathogens. If a grower does not have the technical expertise to properly identify the problem, it is strongly recommended to seek special diagnostician advice. Many countries have plant clinics, and correct identification by experienced diagnosticians can produce excellent results in the routine diagnosis of fairly familiar pests and diseases.

The more often a crop is monitored, the more information a grower has about what is happening in the greenhouse. For an effective IPM programme, greenhouse workers have to be trained to recognize the symptoms of nutrient deficiency, disease, nematodes, mites and insects. In this regard, training of greenhouse workers to identify visible symptoms is of paramount importance in the early detection of abnormalities. Unlike most crops, workers in greenhouse crops have multiple opportunities to visit every plant in the greenhouse (pruning, training,



Plate 29

Training workers and pest control managers in the recognition of insects pests is crucial to IPM success

**Plate 30**

Personal protective gear is mandatory for pesticide operators

harvesting etc.). Their observations could be of great help in the early detection of spot infections or infestation by pathogens and pests. Personal protective gear, disinfectants, disposal bins, markers etc. have to be made available to greenhouse workers so that they can play adequately their role in an IPM programme. In large operations, it is recommended to have a site map of the greenhouses and a good record-keeping system so that disease and pest outbreaks as well as management actions can be noted for the information of all greenhouse staff (IPM is about “teamwork”).

GENERAL GUIDELINES FOR IPM IN GREENHOUSES

The careful integration of all IPM strategies and the implementation of GAP taking account of the various aspects of pest and disease management should follow the guidelines outlined in the four points below. However, if a grower does not have sufficient expertise, it is strongly recommended that the advice of extension staff or a plant clinic be sought.

1. IPM at nursery level

The nursery is the first source of healthy or contaminated planting material with many pests and diseases of greenhouse crops (insects, mites, nematodes, foliar pathogens, soil pathogens etc.).

- Use certified high quality seed.
- Use resistant or tolerant varieties and rootstocks as available in the market.
- Produce seedlings in conditions that ensure vigorous plantlets: a healthy start facilitates implementation of IPM further down the road; if seedlings are contaminated (viruses or soil-borne pathogens) at an early stage, very little can be done after transplanting to save the crop even with the best IPM programme.
- Produce plantlets in a separate greenhouse equipped with very fine mesh on all ventilation openings and a reliable SAS (with foot pad and sponge impregnated with disinfectant), and systematic hand-washing with disinfectant solution by nursery workers and visitors prior to access to the nursery.
- Use only clean or virgin substrate.
- Use adequate irrigation and fertilization management to avoid exposing plantlets to stress conducive to diseases and pests.

- Avoid water saturation and provide an environment suitable for plantlets and unfavourable to pests and pathogens.
- Monitor closely pests, diseases and physiological disorders at all stages.
- Implement strict sanitary measures at all stages:
 - Authorize specialized personnel only to enter the nursery space.
 - Prohibit cigars, cigarettes and chewing tobacco to prevent viral diseases.
 - Do not touch plantlets unless absolutely necessary.
 - Make sure that all equipment (trays, tools etc.) is disinfected to avoid any source of contaminant (there is a major risk of contaminants – pests but most importantly pathogens – in reused trays).
 - Spray growing nursery areas (walkways and benches) with chlorine solutions.
- Apply only registered pesticides as required by GAP protocols.
- Do not raise seedlings directly on the ground or alongside production crops because of the high risks of contamination of transplants from the soil and the crop (common practice among small greenhouse farmers in some countries).
- If the proper infrastructure is not available or nursery expertise is lacking at farm level, acquire good planting material from a certified nursery.
- Take all necessary precautions to avoid exposing plantlets to risks of contamination by pests and diseases during transfer of plantlets from nursery to production greenhouse.

Questions to ask for good decision-making before applying IPM

- What pests and diseases are causing problems and what is their incidence, numbers and stage of development in the specific greenhouse crop?
- What specific conditions might have a direct or indirect effect on the increase or decrease of pests and diseases in question?
- What is the status of natural enemies and antagonists of pests and diseases and are they playing an important role in the regulation of the pests and diseases concerned?
- What is the stage of development, condition of the crop and will it be economical to engage in an IPM programme?
- What management options are available and will their implementation justify the economic cost of the IPM programme?
- If pesticides are the only feasible option, how should intelligent and effective chemical control be implemented following the steps outlined in this chapter?

2. Pest and disease management before planting

Apply strict sanitary measures. Sanitation is by far the most effective and cheapest way of escaping disease epidemics and pest outbreaks. The cliché “it is much cheaper to stay clean than to become clean” applies here.

- Crop residues from the previous crop cycle should be destroyed immediately after the final harvest. The greenhouse should be thoroughly cleaned before planting a new or first-time crop. This means burning, burying or hauling away all leftover roots and other plant material from the previous crop.
- Adequate solarization or soil disinfection (if required) should take place during the crop-free period especially in warm regions. If the above fails to bring soil-borne pathogens and nematodes to a manageable level, the grower is then advised to move to soilless culture.
- All weeds from the greenhouse space should be eliminated before planting as they might harbour some pests and diseases and become the source of contamination of clean planting material.
- Soil and plant debris should be adequately washed from farm equipment when moving from one greenhouse to another to avoid spread of pests and diseases to clean crops.
- Before planting the new crop, growers should thoroughly clean or disinfect the greenhouse structure.
- It is recommended to apply fine 50-mesh (thrips-proof) insect nets to all aeration openings of the greenhouse and to use an SAS at the entry of the production greenhouse to mechanically reduce the chances of insect pests and vectors accessing the greenhouse space. The SAS should be equipped with a foot pad as well as a disinfectant solution for systematic use by greenhouse workers and visitors for disinfecting before entering the greenhouse.



Plate 31

Improved greenhouse tunnel equipped with insect nets, on SAS and side ventilation, to prevent insect pest migration to the greenhouse tunnel (mechanical control) while providing adequate ventilation area



Plate 32

Both SAS and side ventilation of the tomato greenhouse are equipped with a 50-mesh insect screen providing mechanical exclusion of the flying insect pests and adequate greenhouse ventilation

3. Pest and disease management during the crop cycle

Crop rotation is hardly used in greenhouse production systems; in most greenhouses continuous cropping is practised, with or without a very short fallow crop-free interval. Crop schedules are an important factor in IPM. Where there is a risk of disease being more destructive in cool soils (e.g. fusarium crown and root rot and corky root rot), transplanting should be delayed until the root zone has warmed up. Where two or more crops are grown each year, overlapping of planting dates between the different greenhouses and uncontrolled movement of workers between these crops means that pest and pathogen populations are spread from the old greenhouse crops to the young crops, unless special care is taken regarding worker movement between crops.

- Adopt cultural practices to maximize biological and natural prevention of pests and diseases, including: choice of the greenhouse location; use of adequate greenhouse structure with appropriate climate conditions; adoption of good soil management; use of quality water and adoption of irrigation management; use of adequate and balanced fertilization; enforcement of sanitary measures before planting, during production and at the end of the crop cycle.
- Observe proper sanitary measures in and around the production greenhouse before planting and throughout the crop cycle.
- Properly dispose of infected plants or debris (in bins or plastic bags).
- Enforce strict hand-scrubbing rules for workers involved in pruning, pollinating, tying or harvesting activities.
- Use appropriate tools (visual observation, insect colour traps, pheromone traps etc.) for reliable and regular scouting of pests and diseases before and after planting in the greenhouse, in order to make informed disease management decisions (using ET as available), taking into account the quantitative and qualitative assessment of the balance status between pests and diseases and their natural enemies.
- Adopt all possible methods of pest and disease management discussed herein (biological control, physical control, mechanical control, cultural control, biorational pesticides etc.), considering the short- and long-term impact on greenhouse crop productivity and quality as well as the impact on the environment and human health, with the aim of minimizing the use of toxic pesticides.
- Apply safe and intelligent chemical control.



Plate 33

Foot disinfectant pad at the entrance to a greenhouse

Note: Ideally the foot bath should cover all walking space of the SAS.

**Plate 34**

*Example of good agricultural practices
(adequate pruning and plant training)*

With regard to chemical control, it is advised to use only registered pesticides as required by GAP protocols. While other control tactics require fewer precautionary measures, chemical pesticides necessitate the diligent application of precautionary measures, outlined below:

- Use exclusively pesticides registered with the relevant national registration authority and approved for use on the specific greenhouse crop and in line with the GAP protocols.
- Handle, store, apply and dispose of pesticides in accordance with the instructions on the label and in line with the international conventions on pesticides.
- Never transport pesticides, passengers (humans or animals) and food in the same vehicle.
- Only use pesticides when needed and only at the dose prescribed – application of the minimum recommended dose lowers costs and reduces risks of pesticide residues in produce and contamination of the environment.
- Read instructions for application of a particular pesticide before use and carefully consider all information: restrictions for use (beneficial insects, pollinators etc.), application rate, approved doses, compatibility with other substances, mixing properties, minimal intervals between application and harvesting (pre-harvest period).
- Pay special attention to spray equipment, pumps and nozzles used to apply pesticides: to minimize potential risks of over- or under-dosage, accidents and spills, all equipment should be calibrated for accuracy and checked on a regular basis for any malfunction; spray equipment should be washed after each treatment to prevent contamination of produce with compounds not authorized for the specific crop (GAP protocol).
- Keep all pesticides in clearly labelled containers (original containers advised) and store safely away from children, anyone who might misuse them, animals and all water sources. The GAP protocol specifies that containers should be kept in a safe storehouse, which in turn should be: well ventilated; equipped for closing off to prevent unauthorized entry; far from populated areas; on well-drained land; far from domestic water supplies; constructed with non-combustible material; fitted with a leak-proof floor and an emergency exit. Small greenhouse farmers should keep pesticides in a locking ventilated cupboard or cabinet preferably made from iron.
- Absorb pesticide spillage with sand or sawdust and then sweep up and dispose of appropriately; clean the floor with detergent and water.

- Use appropriate masks and protective gear as recommended on the label; personnel must clean and bathe following application.
- Do not spray pesticides in strong wind conditions, especially in naturally ventilated greenhouses, to avoid pesticide drift.
- Adhere strictly to maximum residue limits (MRL) for each pesticide used and for each specific crop. The MRL is the maximum level of residue legally allowed in or on greenhouse produce to provide reasonable assurance that the consumer will have no adverse effects over a lifetime dietary exposure.
- Wash empty pesticide containers multiple times and keep in an appropriate place until disposed of correctly; never put in unused wells or near water sources.
- Make personnel aware of the dangers that can result from improper use of pesticides. Give training in the use and application of pesticides and use of safety equipment and application devices. Inform greenhouse workers that adverse health effects caused by inappropriate use of pesticides are most often not noticeable immediately or in the short term (acute toxicity), but can develop over time (chronic toxicity) if exposure is not reduced. Provide personnel involved in the manipulation of pesticides with the necessary protective gear and appropriate spraying equipment to meet GAP and FAO standards.
- Avoid crop damage: always consult the label as some chemicals may cause phytotoxicity to certain crops under specific conditions; before application, consider the stage of plant development, the pH of the water used in the mixture, the soil type and conditions, the temperature, moisture and wind conditions; make operators aware that phytotoxicity often results from mixing incompatible materials.
- Make safety a priority: follow label directions carefully; avoid splashing, spilling, leaks, spray drift and contamination of clothing; do not eat, smoke, drink or chew while using pesticides; provide for emergency medical care in advance as required by regulations.
- In line with GAP standards and protocol, keep records of pesticide applications.

Pesticide application records

- Date of application
- Greenhouse location or number
- Information on the pesticide (commercial name, active ingredient)
- Dosage and volume of spray applied per unit area
- Operator name for monitoring purposes
- Common name of target pest, disease or weed
- Pest/disease/weed level of infestation or risk as justification for the treatment
- First permitted harvest date

4. Pest and disease management in organic greenhouse production

With the exception of chemical pesticides, the above management techniques apply almost equally to conventional or GAP-certified and to organic-certified greenhouse crop production. While chemical pesticide use is strictly prohibited in organic greenhouse production systems, a wide range of biorational pesticides are allowed. Therefore, many of the above recommendations concerning pesticide use also apply to compounds authorized in organic greenhouse production:

- minerals, including sulphur, copper and diatomaceous earth
- botanicals, including neem, pyrethrum and other new plant extracts
- oils and soaps, including a number of commercially available soap-based products
- pheromones used for monitoring and mass trapping or in sexual disruption techniques
- microbials, including the fast-growing biopesticide products

Appropriate adoption and monitoring of GAP helps improve the safety and quality of food and other agricultural products. It may help reduce the risk of non-compliance with national and international regulations, standards and guidelines, notably of the Codex Alimentarius Commission, World Organisation for Animal Health (OIE) and the International Plant Protection Convention (IPPC) regarding permitted pesticides, maximum levels of contaminants (including pesticides and mycotoxins) in food and non-food agricultural products, as well as other chemical, microbiological and physical contamination hazards.



Plate 35

Organic certified produce: the result of good implementation of IPM, GAP and organic certified produce protocols

Awareness-raising is needed with regard to “win-win” practices which lead to improvements in terms of yield and production efficiencies as well as environment and health and safety of workers. One such approach is integrated production and pest management (IPPM).

Adoption of GAP helps promotes sustainable agriculture and contributes to meeting national and international environment and social development objectives.

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http://archives.eppo.int/MEETINGS/2011_conferences/tuta/FAO_IPM_Near_East.pdf
<http://neareast.fao.org/Pages/Events.aspx?lang=EN&I=104128&DIId=0&CIId=0&CMSId=52&Country=NE&id=898>
<https://www.ippc.int/IP/En/default.jsp>
<http://www.pic.int>
<http://www.fao.org/agriculture/crops/core-themes/theme/pests/code/en/>
<http://www.fao.org/agriculture/crops/core-themes/theme/pests/code/list-guide-new/en/>
<http://www.fao.org/agriculture/crops/core-themes/theme/pests/code/toolkits/en/>
<http://www.fao.org/agriculture/crops/core-themes/theme/pests/jmpr/en/>
<http://www.fao.org/agriculture/crops/core-themes/theme/pests/jmps/en/>
http://www.fao.org/agriculture/crops/obsolete_pesticides/en/

Other important links

<http://ipmworld.umn.edu>
http://en.wikipedia.org/wiki/Integrated_pest_management
<http://www.ipm.ucdavis.edu/GENERAL/links.html>
<http://farmnet.osu.edu/links/ipm.html>
<http://ipm.ifas.ufl.edu/resources/links/index.shtml>
http://www.michigan.gov/mdad/0,4610,7-125-1566_2405_37164---,00.html
<http://ipm.ifas.ufl.edu>
<http://utahpests.usu.edu/ipm/>
<http://ipm.illinois.edu>
<http://www.unce.unr.edu/programs/sites/ipm/>
<http://www.epa.gov/opp00001/factsheets/ipm.htm>
<http://www.landislab.ent.msu.edu/pdf/Landis%20Lab/2008/Gardiner%20et%20al%20Chap%2012%20CBC%20in%20Radcliffe%20IPM.pdf>
<http://www.entomology.umn.edu/cues/dx/chemenu.htm>
http://ebookstore.sony.com/ebook/edward-b-radcliffe/integrated-pest-management/_/R-40000000000000317452
<https://courses.cit.cornell.edu/ipm444/readlist444.html>
<http://www.pic.int>

17. Integrated pest management and farmer education: FAO experiences from the Near East and the Maghreb

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BACKGROUND

General

Integrated pest management (IPM) approaches were first developed in the 1950s. After the Second World War, the predominant thinking in plant protection was that pesticides were the sole answer to pest problems. However, in the 1950s, major pest outbreaks were observed on crops like cotton that had been heavily sprayed following a calendar of regular applications, and pesticide use was challenged as a consequence: the disruption of natural biological control and the development of resistance to pesticides caused a resurgence of pest insects. IPM was a response to situations where chemical pesticides had been perceived as the sole and infallible form of pest control (and such situations predominated in the post-war period).

IPM approaches underline the importance of understanding the biology and ecology of pests and diseases, as well as the complex relations between the different elements of agro-ecosystems, when managing pest populations. In the 1960s, there was increased awareness of the environmental and health problems potentially caused by pesticides, following the publication in 1963 of *Silent Spring*, by Rachel Carson. Since then, IPM approaches have continued to gain importance, albeit with sometimes diverging views on how IPM is best implemented.

Farmers are their own managers, making decisions about which interventions are needed and when. For the implementation of quality IPM, farmers must be ecologically literate. They require knowledge of the main elements of the agro-ecosystem, and they must recognize different creatures and problems, understanding the relations between elements and how specific interventions can influence balances in the system, both immediately and in the course of the cropping season. Farmers often have years of experience and understand

local conditions better than anyone else. However, there may be gaps in their knowledge, especially with regard to pests and their natural enemies, organisms causing diseases, and creatures that are small or not visible to the human eye. Managing such pests is difficult; this is particularly true for the many smallholder farmers that have little access to formal education, to government or private extension services, or to other information sources.

Providing support to farmers to improve their ecological literacy has been an area of attention and activity for many organizations, including the Food and Agriculture Organization of the United Nations (FAO). In the late 1980s, an education approach – the farmer field school (FFS) – was developed as part of an FAO IPM programme on rice in Asia, for farmers to learn about IPM for rice. The FFS approach has since been introduced in over 80 countries and is used to enhance knowledge on IPM for a wide range of crops, but IPM is not the sole focus of FFSs. In 2004, FAO's Regional IPM Programme in the Near East – GTFS/REM/070/ITA – provided support to smallholder farmers to learn about IPM in vegetable and fruit production using the FFS methodology.¹ Some FFSs were conducted with greenhouse farmers, and in some cases, the FFS groups also linked to private GAP systems. The experiences of the IPM farmer field schools are discussed herein, and some thoughts for the future are provided.

Greenhouse vegetable production in the Near East and the Maghreb

In all of the countries in the Near East and the Maghreb, farmers grow vegetables in greenhouses as well as in the open field. However, conditions for greenhouse agriculture vary from country to country, and within countries. Differences exist in ecology and environment (climate, soils, crops, pests and diseases), with implications for production. Socio-economic contexts vary: some farmers are educated in agriculture, have relatively large farms, have the means to invest in their farms and are commercially oriented; while others have small land holdings and limited means to invest, have had limited access to education in agriculture and meet more obstacles to entering markets. Furthermore, smallholder farmers generally have less access to agricultural service providers and to information. However, a steady increase in greenhouse cultivation has been observed in the region, as shown for example in Table 1.

¹ The Regional Near East IPM Programme started in 2004 with six member countries (Egypt, the Islamic Republic of Iran, Jordan, Lebanon, the Occupied Palestinian Territory and the Syrian Arab Republic). In 2009, four more countries joined the project (Algeria, Iraq, Morocco and Tunisia). The programme is supported by the Government of Italy.

TABLE 1
Number of greenhouses and yield (tonnes), Jordan, 2005–11

Crop	2005		2006		2007		2008		2009		2010		2011	
	No.	Prod.	No.	Prod.	No.	Prod.	No.	Prod.	No.	Prod.	No.	Prod.	No.	Prod.
Tomato	7 842	30 137	7 113	32 547	9 531	40 356	11 617	59 874	14 977	88 984	20 355	152 537	21 237	158 507
Cucumber	23 400	105 568	22 649	112 366	28 745	135 086	29 911	135 273	35 881	191 543	37 971	239 781	38 069	244 205
Pepper	4 255	9 924	3 282	7 700	4 972	11 174	5 501	15 268	10 443	25 936	13 676	39 219	13 868	37 939
Beans	2 766	3 461	722	2 044	828	1 876	951	1 794	702	1 432	1 177	3 068	1 127	2 498
Other	7 167	12 422	4 900	9 912	6 338	17 547	3 802	11 218	4 665	13 214	5 656	15 276	5 777	12 235
Total	45 430	161 512	38 666	164 569	50 414	206 039	51 782	223 427	66 668	321 109	78 835	449 882	80 078	455 384

Department of Information, MOA-Jordan

Despite differences, smallholders in the Near East region often face similar problems.

- **Pests and diseases.** (Greenhouse) farmers frequently report problems related to pests and diseases. However, they often have only limited knowledge of what causes the symptoms observed, of the ecology and biology of major pests and diseases. The natural enemy concept is not always understood; how to use biological control and why is not well known. Furthermore, in many cases biological control is simply not available, or not available in time, or perceived to be too costly. Farmers rarely implement systematic monitoring of pests and diseases in greenhouses as the basis for plant protection decisions. This frequently leads to overuse and abuse of pesticides, contributing to economic inefficiencies in pest management, and sometimes causing pesticide residues in excess of acceptable standards. Pesticide residues can affect consumer health and negatively influence market access, especially for export markets (to a lesser extent domestic markets which often do not set standards).
- **Production issues.** There is much room for improving the quantity and quality of production in vegetable greenhouses:
 - Management of fertilization and irrigation systems is often not optimal.
 - Pollination of crops often depends on hormones.
 - Small farmers often have poor greenhouse structures, but there may be scope for improvement with quite simple low-cost interventions.
- **Lack of organization.** In addition to not being very well organized, small farmers have limited access to extension services.
- **Marketing.** Most production is sold in domestic markets, and accessing export markets is difficult for small farmers.
- **Labour.** Family labour is often the main source of labour in the farm, though there might be additional labour hired for specific periods of the season.

**Plate 1**

Greenhouse preparation, IPM/FFS Iraq

The smallholders facing the above problems must make decisions about how to manage crops. In general, they lack practical, hands-on knowledge of IPM and broader production issues. IPM is a suitable and valid basis for organizing training for farmers to improve pest and production management, and the FAO Regional Near East IPM Programme has been doing just this, using the farmer field school approach, since 2004.

MAKING IPM WORK – EDUCATING FARMERS THROUGH FFS

Basics of a farmer field school

An FFS is a season-long non-formal education programme conducted in the field; it brings together a group of farmers (15–25 people) interested in learning about a particular crop. The FFS group sets up a study field on land or in greenhouses belonging to one of the group members in order to experiment new innovative techniques; the results are then compared with those in another farmer field in the area where local practices are used. The FFS meets regularly, normally once a week. During these meetings the participants follow a programme that includes AgroEcoSystem Analysis (AESA), a group dynamics activity and a special topic (see opposite). The FFS is supported by a facilitator trained in strengthening technical and methodological skills. The facilitator can be a field agent from a government service, an NGO or a trained farmer-facilitator. The process in the FFS is always learner-centred and participatory, and relies on an experiential learning approach. Field schools aim to enhance the knowledge and skills of farmers, but also to strengthen social interactions and social capital at community level, and to empower farmers in their daily lives.

Principles of IPM in the FFS

IPM needs to be adapted to meet specific requirements in a location, reflecting ecological conditions, as well as socio-economic and cultural circumstances: a “one size fits all” technical package does not work. In farmer field schools, a set of IPM principles are used to guide a process of validating and adapting ideas and technologies generated outside the community, and to reinforce farmers’ knowledge and skills for making informed field management decisions. The IPM principles are as follows:

- **Grow a healthy crop.** IPM is not limited to pests and diseases, but includes all other aspects of production. The first principle, growing a healthy crop, refers to all relevant cultural practices: soil preparation, variety selection,

A session in a farmer field school

- **AgroEcoSystem Analysis.** AESA is the principal tool in field decisions and it enables a comparison between the local practice (LP) and IPM. Working in small groups of 5–6, farmers make observations in the FFS study fields (IPM and LP). They observe different elements: climatic conditions, soil conditions, plant development, pests and diseases, natural enemies, weeds. They then make a poster summarizing their observations in the field, using mainly drawings. They analyse the situation and discuss the management decisions for the week to come. Each group then presents its findings to the plenary, and all participants discuss what should be done in the IPM field the following week. The facilitator guides the group towards a technically sound decision. AESA helps farmers come to informed decisions, based on field observations.
- **Group dynamics.** The FFS also aims to enhance collaboration between farmers. Group dynamic exercises are held: they are fun and an opportunity to learn about issues such as collaboration, team building and problem solving. Learning points from exercises are discussed and applied to the FFS setting.
- **Special topics.** Special topics are identified together with the group. They may be of a technical nature, but can also touch upon other relevant issues. Whenever possible, they are field-based and experimental.



A. IMPIGLIA, FAO, 2009

Plate 2

Farmer taking notes on greenhouse tomato, IPM/FFS, the Syrian Arab Republic



A. ALHAWAMDEH, FAO, 2017

Plate 3

AESA by farmers IPM/FFS, Jordan



A. ALHAWAMDEH, FAO, 2012

Plate 4

Poster of AESA IPM/FFS, Jordan

Photos from project GTFS/REM/070/ITA-FAO

crop management etc. A healthy crop is better able to compensate for any damage that a pest might cause, and provides the basis for good IPM.

- **Observe regularly.** Regular observations are needed as a basis for informed decision-making. FFSs use AESA as a decision-making tool: all elements of the agro-ecosystem are systematically observed and analysed in order to make an informed decision. Understanding relations between the different elements underpins decisions.

- **Conserve natural enemies and enhance biological control.** In open field systems, natural enemies occur and provide free ecosystem services by controlling pest insects through predation or parasitization. Conserving natural enemies helps to keep pest populations in check, and is an integral part of the decision-making process. Well-designed systems of introduced biological control have been developed for greenhouses to keep pest populations at low levels. Where possible, biological control can be introduced in greenhouses for pest management.
- **Farmers as experts in their exploitation.** Farmers are at the centre of quality IPM. They need knowledge to make good decisions, and they need to know when and where to find additional information and advice when specific (new) problems arise.

The IPM/FFS covers more than pests and diseases, looks at the different production aspects, and emphasizes the role of farmers as expert decision-makers. A curriculum for an FFS is always adapted to the local situation at the preparation stage and during discussion with participants.

Testing and validating IPM approaches

Farmers possess local knowledge and experience in greenhouse management. The FFS provides an opportunity to test and validate different approaches generated by research or other sources, and to adapt them to the local setting. The IPM principles provide a guide for carrying out a comparative study and setting up a learning field (greenhouse). In addition to the FFS's IPM greenhouse, a second greenhouse is used, in which the local practices, commonly adopted in the area, are applied. Weekly AESA observations in both greenhouses allow participants to observe the dynamics and changes, to discuss why differences occur and experiment what seems the best method for a given setting. The FFS provides a space to adapt management strategies to local conditions, taking into account ecological and socio-economic conditions, as well as access to and availability of options. Throughout the FFS, participants collect field data and economic data in order to compare IPM with local practices.

Common problems, local solutions

Managing soil-borne diseases

Soil-borne fungus diseases can be a problem in greenhouses, because of limited possibilities for crop rotation. Several years ago, methyl bromide (MBr) was widely used for chemical soil disinfestation, but due to its negative effects on the ozone layer, it is being phased out. Other solutions include soil solarization, biofumigation, use of antagonists and the use of grafted seedlings. In Jordan, soil solarization (sometimes in combination with grafted seedlings) is used by many farmers in the Jordan Valley, where climatic conditions favour this technique. In other countries, such as Morocco, soil solarization is not feasible, because temperatures are not high enough. The use of grafted seedlings is more common,

sometimes in combination with chemical disinfestation (but not with MBr). In the Syrian Arab Republic, FFSs experimented with techniques including *Verticillium*, an antagonist incorporated in the soil in the greenhouses to reduce disease pressure.

Biological control in greenhouses

In Morocco there are capital-intensive farms producing large quantities of vegetables in greenhouses, often destined for export markets, and certain standards of quality must be met. Biological control programmes are quite common: commercial firms produce the natural enemies needed and provide technical support. However, smallholders in Morocco have less access to such programmes: they might not have enough information, or may lack the required knowledge or perceive biological control as too costly. FFSs introduced some programmes to find out what might and might not work in a smallholder context. In Jordan, biological control programmes in greenhouses are not very well developed; this could be due to the very high temperatures which hamper natural enemies.

Types of greenhouse

The types of greenhouse vary. Some farmers invest in large sophisticated greenhouses (i.e. multispans greenhouses) in which climatic conditions can be controlled relatively easily. Others have simple plastic tunnel greenhouses made of rudimental material. Adaptations can be made to include insect-proof netting to keep out pests, or to install a simple double-door system. Simple improvements can be introduced to better ventilate the greenhouse – very important for managing certain fungal diseases.

Tuta absoluta – tomato leafminer

Several years ago, a new pest was introduced in the Maghreb and it then moved to the Near East countries: the tomato leafminer. It spread rapidly in the region, initially causing substantial damage and losses for tomato growers; it was a major cause for concern. Attempts to control the leafminer with pesticides were not successful due to the biology of the insect. On the other hand, IPM gave good results: the introduction of pheromones, combined with mass trapping,



A. INPIGLIA, GTS/IREM/07/017A-FAO, 2009

Plate 5

Preparation of soil solarization, IPM/FFS Iran (Islamic Republic of)



A. ALHAWAMDEH, GTS/IREM/07/017A-FAO, 2012

Plate 6

Larva of lady beetle feeding on aphid, IPM/FFS Jordan

***Tuta absoluta* IPM strategy, Jordan**

- Early monitoring before planting the crop; this was easily performed by FFS farmers who had been well trained in scouting and monitoring the insect by a specialist who had visited Morocco to exchange knowledge and learn from their experience.
- Distribution by NCARE (National Center for Agricultural Research and Extension), with the support of the IPM/FFS regional project, of more than 20 000 pheromone traps for *Tuta*; these were monitored by farmers and facilitators, while farmers ensured that greenhouses were fully closed to prevent the insect from entering.

rapidly reduced the pressure of *Tuta*; biological control programmes have been successfully implemented in Morocco, but not yet in Near East countries.

In Jordan, the Regional IPM Programme in the Near East implemented a compact strategy to control *Tuta absoluta*. By the end of the first year of the introduction of this insect, two groups from Morocco and Algeria visited Jordan and met with farmers to discuss the best way to manage the pest (farmers were already meeting regularly to discuss the status of the insect in their fields so as to be prepared in the case of an outbreak). Members of the project team participated in two regional symposia for IPM of *Tuta absoluta* to share experiences among project members and exchange knowledge, to then be integrated into activities with farmers. The

FFS farmers play an important role in helping the MOA (Ministry of Agriculture) and NCARE record the first appearance of the insect each year by properly using pheromone traps. Based on the population density, they then apply microbial pesticides (e.g. Bt) and record the results. An FFS (now an association) takes the lead, and after receiving the pheromones from the ministry, they distribute them to other farmers in the same area and ensure proper monitoring using the traps, recording findings and following up as necessary.

Bumblebees

Many farmers use growth hormones to pollinate the crop: bumblebees are an alternative and tomatoes pollinated by bumblebees are of better quality. However, there are constraints: bumblebee hives are not always available when they are needed and they can be costly.



A. ALHAWAMDEH, GTFS/REMI070/ITA-FAO, 2011

Plate 7

Bumblebees, IPM/FFS Jordan

Post-harvest crop waste and residues

When a crop is harvested, there is often produce that is of insufficient quality for marketing. Farmers typically leave most of this behind in the greenhouses, between the rows. In FFSs in Jordan, farmers discuss the importance of this waste – a potential source

of diseases and pests in the subsequent season. They start to collect it, burn it, use it for compost, or just remove it from the farm. Some farmers start to grade their harvest, using the lower quality produce for third or fourth grade marketing.

SOME RESULTS OF IPM IN GREENHOUSE FFSS

With the support of the Regional Near East IPM Programme, FFSSs have been organized in the ten countries covered by the project (Algeria, Egypt, Iraq, the Islamic Republic of Iran, Jordan, Lebanon, Morocco, the Occupied Palestinian Territory, the Syrian Arab Republic and Tunisia). Since 2004, approximately 1 100 FFSSs have been organized on a range of vegetable and fruit crops (tomato, cucumber, watermelon, mint, grape, strawberry, date palm, apple, citrus, olive), and about 16 000 farmers have been trained in IPM and good agricultural practices (GAP), about 10 percent of whom are women. Also FFSSs were organized on greenhouse crops – cucumber and tomato in particular – in several countries, and an overview is given below. For additional information on other project activities, see www.ipm-neareast.com. Table 2 shows the FFSSs organized for greenhouse crops under the FAO GTFS/REM/070/ITA Project for the period 2004–12.



A. EZAMI, GTFS/REM/070/ITA-FAO, 2011

Plate 8
Facilitator with farmers, IPM/FFS Iraq

TABLE 2
Number of greenhouse FFSSs implemented by the Regional Near East IPM Programme, 2004–12

Country	Number of FFSS	Number of farmers trained
Greenhouse cucumber		
Iran (Islamic Republic of)	21	256
Iraq	3	42
Jordan	29	406
Occupied Palestinian Territory	9	139
Greenhouse tomato		
Algeria	9	27
Iraq	3	42
Jordan	14	200
Morocco	4	38
Occupied Palestinian Territory	21	331
Syrian Arab Republic	31	490
Tunisia	8	144
Total	152	2 115

During the FFSs, records were kept for a set of indicators to enable a comparison between local practices and IPM practices in the FFS study plots. The indicators include information on pesticide use, use of fertilizers, yields and economics. Results for FFS activities in greenhouses from the project database are summarized below.

Information is also provided on pesticide use, use of fertilizers, yields and economics, comparing IPM and LP fields in the greenhouse FFSs in different countries. The data were collected by facilitators, and were included in the regional project database. Data for the Maghreb countries are based on a limited number of FFS activities implemented in the period 2010–11.

Greenhouse tomato

Chemical pesticide use in the region is reduced from an average of 19.4 applications per season under LP to 7.4 applications under IPM. The use of biopesticides increases from 0.1 applications in LP to 0.6 in IPM. Naturally, quite large differences exist between countries: in Morocco greenhouse tomato is a very intensive culture, and averages are higher than in other countries. However, in all countries a substantial reduction (41–71 percent) in the use of chemical pesticides can be observed in the IPM plots.

Solarization was widely used in the Near East countries to manage soil-borne diseases, but not in the Maghreb (due to differences in climate and cultural practices). In the IPM plots in the three Near East countries, 45 fields out of 64 used solarization, compared with 16 fields out of 64 under LP. Methyl bromide was used in none of the 64 IPM fields, against 28 of the 64 LP fields. In the Syrian

TABLE 3

Average pesticide use in IPM and LP (local practice) FFS study fields – number of applications per season, greenhouse tomato, 2004–11

	Region		Algeria		Jordan		Morocco		Occupied Palestinian Territory		Syrian Arab Republic		Tunisia	
	IPM	LP	IPM	LP	IPM	LP	IPM	LP	IPM	LP	IPM	LP	IPM	LP
Insecticides	2.9	8.7	0	4.5	3.6	7.8	11.0	24.5	5.3	14.0	0.7	4.7	1.0	4.0
Fungicides	3.7	8.7	6.5	6.5	3.3	6.8	12.0	38.0	4.7	10.8	2.7	6.5	2.0	4.0
Herbicides	0.2	0.4	0	0	0	0	0	0	0.6	1.4	0	0	0	2.0
Other pesticides	0.6	1.7	0	0	1.2	3.6	2.5	2.5	1.4	0.5	0	0.4	1.0	2.0
Total chemical pesticides	7.4	19.4	6.5	11.0	8.0	18.2	25.5	65.0	11.0	26.7	3.8	12.8	4.0	12.0
Biopesticides	0.6	0.1	0	0	0	0	9.5	2.5	0.5	0	0.3	0.1	0.3	0.1
Total applications per season	8.0	19.5	6.5	11.0	8.0	18.2	35.0	67.5	11.5	26.7	4.1	12.9	4.3	12.1

TABLE 4

Average fertilizer use in IPM and LP study fields, greenhouse tomato, 2004–11

	Jordan		Morocco		Syrian Arab Republic	
	IPM	LP	IPM	LP	IPM	LP
N (kg/ha)	253	430	680	680	134	263
P (kg/ha)	215	339	390	390	143	322
K (kg/ha)	156	290	575	575	143	327
Organic fertilizer (kg/ha)	771	792	50 500	50 500	14 097	14 121
Soil analysis	11/14	0/14	0/2	0/2	24/31	8/31

TABLE 5

Average yields (kg/ha) and economics (USD/ha) in IPM and LP study fields, greenhouse tomato, FFS data 2004–11

	Region		Jordan		Morocco		Occupied Palestinian Territory		Syrian Arab Republic	
	IPM	LP	IPM	LP	IPM	LP	IPM	LP	IPM	LP
Yield (kg/ha)	152 626	143 268	53 721	53 804	166 500	164 900	152 619	149 548	190 022	172 250
Value production (USD/ha)	40 687	37 292	16 098	15 579	77 254	77 333	10 084	9 234	57 837	52 224
Costs production (USD/ha)	16 649	17 291	11 978	13 470	30 231	37 044	3 745	4 543	21 649	21 466
Benefits (USD/ha)	23 585	19 624	4 120	2 109	47 023	40 290	6 340	4 691	36 188	30 758

Arab Republic, MBr was used in 24 (out of 30) LP study fields, while biological control was used in 26 (out of 30) IPM study plots, compared with just 1 LP plot.

For greenhouse tomato, fertilizer use in IPM study fields is lower than in LP; however, the organic fertilizer amounts are similar. In the region as a whole, average yield levels in the IPM fields are higher than in the LP, with variations at country level. The IPM fields produced more benefits than the LP fields, as a result of the lower production costs and/or a higher production value.²

Greenhouse cucumber

In the region, chemical pesticide use is reduced from 16.8 applications per season to 7.0 applications. The use of biopesticides in IPM is somewhat higher than in LP: 0.2 versus 0.1 applications. Differences exist between countries. However, in all cases the use of chemical pesticides in IPM is substantially reduced, by between 53 and 65 percent.

² Yields in Jordan are lower than in the other countries due to the particular climatic conditions in the Jordan Valley.

Solarization was widely used to deal with soil-borne diseases. In the IPM plots, 50 out of 58 fields used solarization, compared with 29 out of 58 fields under LP. Methyl bromide was used in none of the 58 IPM fields, and in 3 of the 58 LP fields. Data collected after mid-2009 show that none of the LP fields used MBr. Soil analysis is used frequently in the IPM study fields, allowing for a reduction in the use of chemical fertilizers.

In Jordan, average yields levels in IPM are slightly lower than in LP, while they are higher in the Occupied Palestinian Territory. Benefits in the IPM fields are higher than in the LP fields, due to lower production costs and/or a higher production value.

TABLE 6

Average pesticide use in IPM and LP FFS study fields – number of applications per season, greenhouse cucumber, 2004–11

	Region		Iran (Islamic Republic of)		Jordan		Occupied Palestinian Territory	
	IPM	LP	IPM	LP	IPM	LP	IPM	LP
Insecticides	3.4	8.3	1.8	5.5	4.7	10.0	3.9	10.0
Fungicides	2.8	6.6	1.5	4.7	3.8	7.7	3.2	8.1
Herbicides	0	0	0	0	0	0	0.1	0.1
Other pesticides	0.7	1.8	0	0	1.4	4.0	0.4	0
Total chemical pesticides	7.0	16.8	3.3	10.2	9.8	21.6	7.7	18.2
Biopesticides	0.2	0.1	0.3	0.2	0	0	0.9	0
Total applications per season	7.2	16.9	3.6	10.4	9.8	21.6	8.6	18.2

TABLE 7

Average fertilizer use in IPM and LP study fields, greenhouse cucumber, 2004–11

	Iran (Islamic Republic of)		Jordan	
	IPM	LP	IPM	LP
N (kg/ha)	139	483	248	355
P (kg/ha)	2	105	215	319
K (kg/ha)	10	135	183	326
Organic fertilizer (kg/ha)	30 714	29 524	704	673
Soil analysis	10/10	10/10	17/29	0/29

TABLE 8

Average yields (kg/ha) and economics (USD/ha) in IPM and LP study fields, greenhouse cucumber, FFS data 2004–11

	Jordan		Occupied Palestinian Territory	
	IPM	LP	IPM	LP
Yield (kg/ha)	62 481	64 208	85 167	67 611
Production value (USD/ha)	15 642	15 944	4 789	4 305
Production costs (USD/ha)	11 450	13 168	1 842	2 238
Benefits (USD/ha)	4 192	2 776	2 947	2 067

SOCIAL CHANGE

Farmer field schools allow farmers to compare IPM and local practices, and to evaluate technical and economic differences. Farmers report additional gains obtained from their FFS experience, including, among others, improved cohesion and collaboration with other farmers, increased self-confidence, and better linkages with government/NGO staff. Examples of other reported positive developments are detailed below.

Social capital strengthened in FFS

Farmers become facilitators. In most of the project countries farmers have become facilitators. Following participation in an FFS, they indicate interest in organizing an FFS for others in the community. With additional training and support, farmer-facilitators play a key role in their community to train others, and take a lead in community development (see below).

Farmer-facilitators

Jordan

Ms Lema Noem is a Jordanian farmer who has been involved in IPM/FFS activities since 2004. She was trained to become an IPM/FFS facilitator for one group of greenhouse tomato growers in her village. At the time, she was working with her father on his farm: young, with limited experience and no experience at all of dealing with other farmers. She joined the training, gained knowledge on technical issues and improved her self-confidence. Her first FFS was with 12 farmers (including 5 women). In the second year, she facilitated a group of 14 female farmers. Neighbouring farmers then began asking her for advice on crop and pest management. In 2007, her father died and her family asked her to manage the family farm. Now, she is a leader and a focal point in the area. She recently established an association in the village for female farmers to provide support to women in agriculture.

Syrian Arab Republic

Mr Masheer Al Rihea is a greenhouse tomato grower living in Ras Al Ein village, Lattakia Province. After attending an IPM/FFS as participant, he was selected to be a facilitator to train other farmers in the village. "In 2005," Mr Al Rihea says, "I used to rely on pesticide companies to know what I had to spray. I reached up to 30 sprayings a season. When I joined the FFS group, I learnt about IPM and alternatives to pesticides. Then, I learnt a new technique to me, called the Agro-Eco System Analysis (AESAs), to monitor my crop regularly and to consider all factors related to the crop, such as weather conditions, stage of the crop's growth, and pest developments. I eliminated the use of insecticides by introducing biological control. I can say that I improved my decision-making skills through the participatory approach adopted by the FFS. Then, I conducted FFS for my people of the village, I was so happy when they decided to join the FFS."

A. ALHAWAMDEH, GTFS/REM1070/ITA-FAO, 2012

**Plate 9***Plant observation by farmer, IPM/FFS Jordan*

N. AYDI, GTFS/REM1070/ITA-FAO, 2012

**Plate 10***AESA preparation by farmers, IPMIFFS Tunisia*

Farmers create associations, marketing groups

The FFS experience leads to the creation of associations (see below).

Associations

Morocco

In Morocco, a group of farmers who had participated in an IPM/FFS, created two associations when the FFS came to an end. Producers of mint in Laghnimyine and Beniyagrine are now organized in associations that help them to better access subsidies for the acquisition of agricultural inputs (biocompost, biopesticides) and small equipment (small tools, sprayers, mechanical harvester).

Jordan

In Jordan, four groups of farmers who had participated in an IPM/FFS, created four associations following two years as FFS members. Two are for female and the other two for male farmers. These associations help farmers in different ways. They may have the ability to control and monitor water distribution in their area, or they may seek opportunities to bring their products to new markets, for example, by processing their products and finding new ways to market products such as cucumber and tomato.

Farmers linking with consumers

The FFS experience does not stop at the farmer. The FAO Near East project also helped establish the link between farmers and consumers: marketing skills for farmers, healthier products for consumers (see below).

From farmers to consumers

- 2010, IPM Group established in the Islamic Republic of Iran, with support from the Regional Near East project, to help smallholder farmers better market their IPM products, while helping consumers access healthier food.
- Membership currently over 300.
- USD100 (approx.) membership fee contributed by every member to cover initial administrative costs.
- Linkages (direct and short) promoted between producers and consumers leading to a relationship based on trust – no formal certification.
- Direct sale of IPM products from producer to consumer through the Group, with objective of enlarging the network and formalizing collaboration with farmers' and consumers' cooperatives.
- January 2011, shop space allocated by the Municipality of Tehran to the IPM Group inside one of the public fruit and vegetable markets in the north of Tehran.
- February 2011, space allocated to the IPM Group within the Iranian Research Institute for Plant Protection's consumer cooperative store for the promotion of IPM products.
- Current objective: expand activities in Tehran and other provinces.
- Other activities: organization of seminars, short trainings and information days on relevant subjects for members.

CONSTRAINTS AND CHALLENGES IN IPM/FFS PROGRAMMES

IPM/FFSs build a good understanding of ecology to help strengthen knowledge and skills and they allow farmers to modify their practices, for example, reducing the use of pesticides and increasing fertilizer-use efficiency, resulting in similar or slightly improved yield levels and greater benefits. In the FFSs on greenhouses, efforts have been made to introduce and enhance biological control. Farmers learn about the larger production system, as well as about pest management. IPM/FFSs provide a doorway towards sustainable crop production intensification – the “Save and Grow” approach promoted by FAO www.fao.org.

Nevertheless, there are constraints, and the programmes continue to face challenges (listed below).

- Farmer field schools require time and resources. Facilitators need to be trained to have appropriate technical and facilitation skills, and they need to be available to conduct the FFS. Sufficient time is needed to prepare the FFS. Farmers need to be informed and convinced to join. The local production system needs to be understood in order to design a curriculum relative to the precise context.
- Quality of farmer field schools is the key to its success. Active support is needed during the season to identify problems and to overcome them, whether technical or methodological. Refresher courses are required for facilitators to update their skills regularly.
- Access to bumblebees and biological control can be difficult for farmers, even when they are aware and convinced of the advantages. Biocontrol agents are not always available (or not available in time) and can have high costs, and quality problems may arise in some places. In some areas, commercial companies provide biocontrol, in others there is a government service. In the latter case, natural enemies may be provided free of charge or at a nominal price, but there might be a limited capacity and planning for the production and delivery of biocontrol agents to interested farmers. For IPM in greenhouses, in particular, biological control provides a technically sound alternative to pesticides, and should be made increasingly available also to smallholders.
- Enabling environment. Even when farmers are convinced of the usefulness of IPM, they continue to meet constraints. Contradicting messages or programmes can arrive from the government or private sector, leading to confusion for farmers. In some countries, FFSs have been integrated into government programmes; in others, FFSs are taken up by different projects.
- Marketing. Many trained farmers reason that IPM products are of higher quality, since they are produced with fewer pesticides, and they therefore expect to obtain premium prices. This is often not the case. Certification for IPM is not common in the area, and where it does exist, standards are not always very well defined or protected. Linking to existing (private) certification systems, such as GAP, could be a solution.

Linking IPM with GAP systems

Good agricultural practices (GAP) systems have been gaining ground in recent years. In the Near East and the Maghreb, the private GLOBALG.A.P. system, developed by major supermarket chains, is in place in some countries.

Numerous FFS groups wish to gain better access to markets. Linking with GLOBALG.A.P. is an option, and efforts have been made to achieve this. Some

of the FFS groups in the Occupied Palestinian Territory underwent additional training to become GLOBALG.A.P. certified. For smallholder farmers, however, there are constraints to becoming certified for GLOBALG.A.P. (see below).

It remains a challenge for smallholders (trained or untrained) to become GLOBALG.A.P. certified. However, at the same time, products for domestic markets do not necessarily have to meet quality standards. Developing GAP standards endorsed by ministries to ensure good practices in agriculture, guarantee a minimum set of standards to protect both producers and consumers, and enhance proper conditions of work in farms could be an appropriate approach for the Near East and the Maghreb region. The ASEAN GAP for fruits and vegetables could serve as an example.

Constraints to GLOBALG.A.P. certification

- The cost is perceived as an obstacle.
- Smallholders may only be able to deliver limited quantities of produce.
- Group certification, although cheaper, requires good organization – often lacking with small farmers' groups.
- Certification requires regular renewal, for a fee.
- Farmers lack confidence that the certification will pay off: they fear not being able to sell their produce at better prices, whether sales are destined for export or specialized domestic markets; they fear having to sell their products in the domestic market at the same price as non-certified products.
- Investments in farm infrastructure required to meet GLOBALG.A.P. requirements can be problematic for smallholders.

THOUGHTS FOR THE FUTURE – PROMOTING IPM AND GAP IN THE REGION

- Stimulate a regional discussion on GAP for fruits and vegetables with the aim of enhancing more sustainable crop intensification and promoting a minimum set of standards of production and working conditions to protect producers, farm workers and consumers both within and outside the region.
- Actively promote ecological literacy among farmers, in particular smallholders, to develop the knowledge and skills needed to produce high quality fruits and vegetables. Ensure that relevant government NGO staff receive the necessary training to guide a process of learning.
- Identify enabling policies to enhance GAP, and take necessary action.

18. Harvest and post-harvest management

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INTRODUCTION

Farmers grow horticultural crops to make money. To be successful they must deliver products to buyers who are so pleased with the quality and value of that product that they will purchase them again and again. Growers must therefore continuously satisfy consumer needs and desires for fresh greenhouse-grown products by using all the available technology and knowledge to produce, harvest, package, store, transport and market their products.

Production should be consumer driven. Growers need to comprehend the nature of the market where they sell their products. They must understand the factors that influence product quality and affect deterioration after harvest. Delivery of greenhouse-grown vegetables and fruit must be seen not only as a source of food and nutrition, but also as a service providing wellness and good health for families.

While crops may be sold in the local village or on a nearby market, most crops are sold far from the production sites, in major cities or at faraway markets. This means that produce has to be harvested, sorted, packed, stored and transported to storage facilities or markets, with sales often taking place several days or sometimes weeks after harvesting. Therefore growers, agents, wholesalers and retailers will always be concerned about maintaining quality and minimizing post-harvest losses that may occur in the chain from grower to consumer. Quality of the end product can only occur when there is a realistic, integrated and coordinated linkage between the stages in the supply chain.

WHAT IS QUALITY?

We all think we know what a quality product is when we see it. In practice, quality always lies in the eyes of the beholder. A quality product for a farmer will be different from a quality product for a retailer, a rich sophisticated housewife or a poor malnourished child. Each has their own perception of quality. Quality

is sometimes defined as fitness for purpose. Adel Kader and Rosa Rolle (2004) have defined quality as “the degree of excellence or superiority comprising a combination of attributes, properties or characteristics that give each product value in relation to its intended use”. Herein, quality is defined according to particular market or country grade standards. Thus, external attributes such as size, weight, colour, shape and freedom from physical, physiological and pathological defects are key factors, as are internal attributes, such as texture, taste, aroma and chemical composition (nutritional and health-conferring compounds) that are very difficult to measure objectively and non-destructively. The extent to which these dominate depends on the nature of the market. However, it is the end-user who ultimately decides on quality; if they purchase a product, then its perceived (often external) quality satisfies them at the time. If the internal quality of the product is unsatisfactory when consumed, then it will not be purchased again on the next visit to the retailer. The challenge faced by producers is to provide consistent quality such that the consumer is entirely satisfied and makes repeat purchases of that farmer’s product or brand.

In general, consumers judge quality and choose to buy on the basis of the appearance of the product, while subsequent purchases are based on their satisfaction with the internal attributes of the product, such as flavour and texture. In other words, they buy using their eyes and their memory. The most important quality attributes influencing consumer choices include:

- external features – appearance, size, shape, colour, gloss, firmness, freshness;
- internal features – texture, crispness, juiciness, mealiness, toughness, composition, nutritional and health value;
- flavour – sweetness, sourness (acidity), aroma, taste, astringency, bitterness, off-flavours;
- nutritional value – vitamins (C, A, B, thiamine, niacin), minerals, dietary fibre, antioxidants and phytonutrients (e.g. carotenoids, flavonoids, isoflavones and phytosterols);
- freedom from defects – physical damage (cuts, bruises, scars, scabs, russetting), rotting, insect and disease damage;
- safe food – freedom from toxins and contaminants, human pathogens (e.g. *Salmonella*, *Listeria* and *E. Coli*) and chemical residues.

PRE-HARVEST FACTORS AFFECTING PRODUCT QUALITY

Quality at harvest is influenced by a range of pre-harvest factors, including: original planting material, growing conditions, substrate type, nutrient and pest and disease management, and temperature, water and light intensity experienced during plant growth and development. For example, vitamin C is an essential nutrient for humans and comes from fruit and vegetables; its concentration can increase with high light intensity and slight water stress during leaf growth, but

decrease with high nitrogen levels in the growing media (Lee and Kader, 2000). Pre-harvest factors can affect product quality during post-harvest storage. If quality at harvest is not optimum, post-harvest quality and shelf-life are compromised.

A problem with tomatoes and sweet peppers is the physiological disorder, blossom end rot, caused by an interaction of low calcium, high nitrogen and fluctuating water availability during growth. A judicious programme is required to optimize calcium and nitrogen nutrition while applying a management system for consistent water availability and good relative humidity control in greenhouses. Foliar applications of appropriate Ca^{2+} salts may help reduce the disorder as part of a programme to obtain optimum $\text{Ca}^{2+} : \text{N}$ ratios in susceptible plants.

HARVEST

Product quality at harvest time is essential for satisfying subsequent consumer requirements and stimulating repeat purchases. Harvesting stage influences the concentration in micronutrients since many of them (especially carotenoids) accumulate during the whole development process in fruits. For most products optimum quality is attained at harvest time; deterioration then commences and continues inexorably, with quality decreasing through senescence and death.

Harvest maturity

Depending on the intended market there is an optimum stage of maturity for harvesting, specific for each crop and sometimes for varieties within a crop. If harvested when too immature, the product will never attain its full flavour and aroma potential because of low concentrations of sugars and other compounds that increase with maturity; it will be susceptible to mechanical injury, wilting and physiological disorders including chilling injury. If harvested when overmature, the product will senesce rapidly, be soft and mealy with an insipid flavour, be susceptible to post-harvest pathogens, physical damage and loss of desirable texture, and develop bitter off-flavours. Market forces may influence the time of harvest, with undue and unreasonable pressure brought onto growers by supermarkets to provide a product in times of short supply, even though inherent quality may not be optimal. Care must be taken to ensure that long-term market prospects are not jeopardized by supplying immature products that will have a negative effect on ongoing consumer purchases.

With most crops, fruits generally ripen sequentially up the plant; multiple harvests ensure that fruit of uniform and optimum maturity is harvested at any one time, facilitating regular and continuous supplies to market. In general, products should be harvested in the early morning while temperatures are still relatively cool. Peppers, melons, tomatoes and cucumbers should be cut from the plant with sharp scissors or a knife. Care must be taken to avoid physically damaging products during harvest operations or in the containers used to transport them to the packing facility.

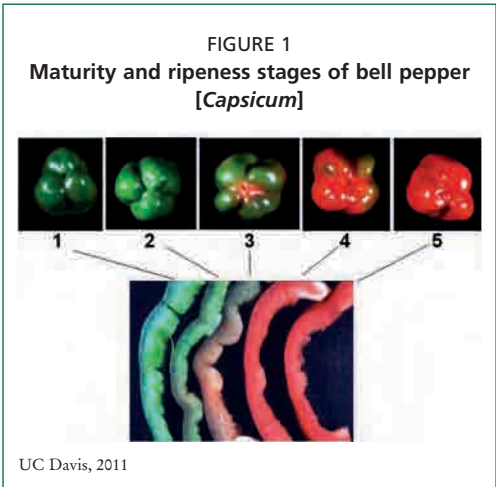








FIGURE 2
Maturity and ripeness stages of tomato

	1. Green Tomato surface completely green although shade may vary from light to dark green
	2. Breaker Definite break in colour from green to tannish-yellow, pink or red on ≤ 10% of fruit surface
	3. Turning Definite change in colour to tannish-yellow, pink or red colour on 10–30% of fruit surface
	4. Pink Pink or red colour shows on 30–60% of fruit surface
	5. Light red Pinkish red or red colour shows on 60–90% of fruit surface
	6. Red > 90% of fruit surface is red in aggregate

www.floridatomatoes.org

Bell pepper (Capsicum)

Bell peppers are normally harvested when they have achieved full size and the cultivar’s characteristic colours: green, yellow, purple or red (Figure 1). Market requirements dictate at what colour stage fruit is harvested. Fruit must be of uniform shape and free from defects, such as blossom end rot, cracks, decay or sunburn.

Tomato

Tomato is a climacteric fruit and can ripen satisfactorily when harvested at the mature green or breaker stages (Figure 2), although it will never attain the sweetness or flavour of fruit harvested at the light red or red stages, as it has not been able to accumulate as much carbohydrate from photosynthesis as has more mature fruit that has spent longer on the vine. The final decision as to the stage of maturity appropriate for harvesting depends on the market location. The closer the market is to the site of production, the more mature the fruit may be. The corollary is that fruit destined for export to a distant market must be harvested at a less mature stage.

In many countries, fruits harvested at the mature green or breaker stages are treated subsequently with ethylene (100 ppm, at ~20 °C, 90–95% RH, for 24–72 hours) in a room with good air circulation to prevent buildup of CO₂. Fruit harvested at stages 5 or 6 has enhanced taste and flavour compared with early harvested fruit, but also reduced shelf-life, softening more quickly and being more susceptible to physical handling, transport damage and rots. Fruit can be harvested once seeds are fully developed and gel formation is apparent in at least one locule. It should be noted that any modern long-life varieties with extended shelf-life traits, resulting from the presence of the *rin*

or *nor* gene, should not be harvested until at least the pink maturity stage, when at least 30 percent, but no more than 60 percent, of the fruit surface is a pink-red colour.

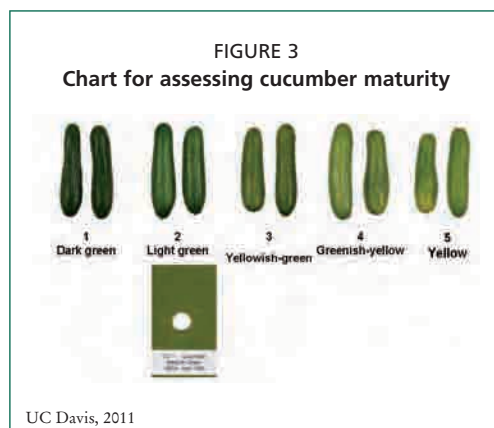
Increasingly diverse offerings are being made available; they generally add value for the grower and provide more convenience for the consumer. Tomato trusses are increasingly used (Plate 1), often in their own convenient package. A number of varieties are now available that mature and ripen relatively evenly along the truss and have a relatively long shelf-life. This means that they can be harvested at a more mature stage than traditional varieties, have higher nutritional value and higher dry matter content, and thus have enhanced taste and flavour and are consequently more likely to be favoured by consumers in repeat purchases. Value can also be added by diversifying packaging.



Plate 1
Tomato fruit trusses where fruit is of uniform size and colour

Cucumber

Cucumbers are harvested as a physiologically immature but edible fruit, near full size and before the seeds are full size or hard. Fruits are edible at most developmental stages. At optimal harvest maturity, a jelly-like material forms in the seed cavity. Firmness and glossiness also indicate imminent harvest maturity. Fruit should be uniform in shape and size, firm with a dark green colour, free from defects and no signs of yellowing should be visible (Figure 3).



Green bean

Green beans are immature fruit vegetables, harvested while still developing and growing rapidly, when the fruit is bright green, the pod is fleshy and seeds are small and green. They should be well-formed, straight, fresh in appearance, tender but firm, and should snap easily when bent. Pods should be smooth and without bulges from the seeds inside.

Eggplant (aubergine)

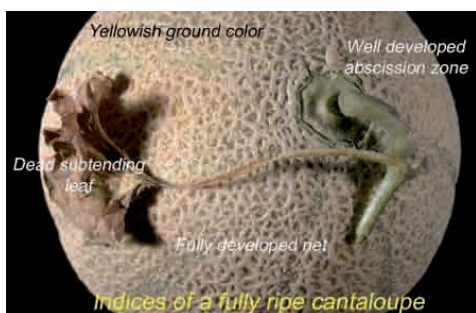
Eggplant fruits are harvested at a range of developmental stages depending on the cultivar (Plate 2), but generally when



Plate 2
Range of eggplant types

immature, before seeds enlarge and harden. Normal quality indices apply, such as size, characteristic shape, skin colour, freedom from defects and presence of a fresh green calyx.

FIGURE 4
'Cantaloupe' melon: fully ripe melon



UC Davis, 2011

Melon

There are many melon cultivars, some of local origin and grown traditionally; each have their own specific maturity attributes and are not normally harvested according to size (Figures 4 and 5). As with other fruits, harvesting at the correct stage of maturation is important to allow them to store and retain eating quality right through to the final consumer. Some important types grown in Mediterranean countries include: 'Cantaloupe', 'Galia', 'Charentais',

FIGURE 5
'Cantaloupe' melon: stages of ripeness



1. Full-size melon, no slip: "pull" fruit
2. Slip just starting, near $\frac{1}{4}$ slip: requires high thumb force to push stem from fruit
3. $\frac{1}{2}$ – $\frac{3}{4}$ slip: melon can be pushed with moderate thumb pressure from stem
4. Full slip, stem scar with fresh appearance: stem easily pushed from fruit
5. Slip occurred day prior, very dry stem end: melon may be soft

UC Davis, 2011

‘Crenshaw’ and ‘Honeydew’. ‘Cantaloupe’ fruits are harvested at $\frac{3}{4}$ to full slip when a definite abscission zone (“slip”) has developed. Fruit should be firm with a raised and well-formed netting on the surface. Depending on the cultivar, skin colour varies from dull green to deep green at maturity and light yellow at ripeness. Harvest maturity is difficult to assess on honeydew melons as no clear abscission zone forms. Maturity is normally judged by changes in ground colour from green to cream.

Lettuce

Lettuce in greenhouses will generally be produced hydroponically using specialized high value cultivars of varied colour, size and degree of heart formation. In most cases they will tend to consist of loose leaves rather than a firm or hard head; in other words they will be less developed than the traditional crisp or ‘Iceberg’ types. Such less developed lettuce plants will have better flavour than overmature heads that will tend to be bitter and less sweet.

In many cases, lettuce will be harvested when leaves are the typical colour for the cultivar, not wilted and free from defects such as tip burn. Whole plants can be harvested with intact roots (Plate 3) and placed in plastic bags or containers, so they remain “alive” through the supply chain until they reach the home of the consumer. It is important for growers to determine the market requirements of size, colour, type and optimum production time in order to optimize sales and profitability. In addition, a large proportion of lettuce is destined for the restaurant trade and is prepared as “fresh cut” or loose leaves in polymeric film packages.



Plate 3

Lettuces growing hydroponically (left); harvested with roots attached (right)

Harvesting operations

While harvesting is dependent on planting dates and environmental conditions during growth, the harvesting operation must nevertheless be well planned and coordinated with a comprehensive packaging, storage and marketing strategy organized well before harvesting commences. Staff must be well trained to consistently harvest only those products at the correct stage of maturity for the intended market. Staff must adopt good hygienic practices with clean hands, removal of rings, and short fingernails to avoid making cuts in the product while harvesting. All products must be handled gently to avoid surface damage.

Tools for harvesting must be clean, sharp and well maintained to minimize injury. Cutting implements (knives, scissors, secateurs) should be rinsed regularly in disinfectant solution to avoid cross contamination of any diseases.

Harvesting should be done early in the morning to reduce the field heat load of the crop. At this time fruit will be fully turgid having accumulated water during the night and can be very susceptible to mechanical damage if not handled very gently during harvesting and transport to the packhouse. Most crops need to be harvested on more than one occasion as the fruits attain the appropriate maturity. Once harvested, products should be shaded from direct sunlight to prevent heating from direct radiation and respiration heat, both of which hasten deterioration. Time between harvest and initial cooling must be minimal, as greenhouse crops are very perishable, and respire and transpire at high rates at normal greenhouse temperatures.

All products must be harvested carefully and placed gently into appropriate containers to avoid any physical damage (bruises, cuts) that may lead to increased loss of water and vitamin C. Any vertical drop of more than 25 cm will result in bruising for most perishable greenhouse crops. Physical damage leads to production of ethylene in some crops, entry of post-harvest pathogens and increased susceptibility to post-harvest rots. Containers must not be too deep to avoid compression damage of soft products, and they should have smooth sides, no sharp edges, and must be kept clean and sanitized prior to reuse to prevent development and spread of disease organisms.

Mechanization is being increasingly developed in harvesting aids. A recent innovation is the production of a new container for capsicums with an automatically movable bottom plate that sinks into the container as more capsicums are added to the top of the container. Each container has two sections, is 2.5 m in length and can hold about 300 kg of fruit (Plate 4). Other automated or semi-automated systems exist for different greenhouse configurations and crops (e.g. overhead moving conveying systems).

As soon as containers are full, they should be immediately removed from the greenhouse and taken to the sorting and packing zone of the complex.

They must be removed from the heat of the greenhouse and direct sunlight to a zone where the product (field) heat can be removed quickly. Some products, including tomatoes, peppers and aubergines, may be packed directly into their final containers in the greenhouse, but this depends on the product type, the uniformity of the product and the nature of the intended market.



Plate 4

A new “automatic” harvest container developed by Buitendijk Slaman BV for capsicums and other greenhouse crops

Harvesting – Summary and GAP recommendations

- Maturity at harvest must be such that the product reaches the consumer at optimum eating quality.
- Harvesting too soon results in susceptibility to decay, water loss and lack of sugars.
- Harvesting too late results in premature senescence, susceptibility to decay and over-ripe product with decreasing taste, flavour and texture.
- Each product has its own optimum harvest maturity depending on the location and on the distance and transport time from the production site.
- Great care must be taken to avoid physical damage to products during harvest and transport to the packing facility, as cuts, bruises and scarring will lead to pathogen infection.
- Tools used for harvesting must be clean, sharp and sanitized regularly.

TEMPERATURE MANAGEMENT

The quality of greenhouse-grown crops is dictated by two main factors:

- physical damage sustained during harvesting and transport; and
- temperature management.

The best way to maintain post-harvest quality and reduce deterioration is to reduce product temperatures to levels that are optimal for the specific crop. There are two separate sides to temperature management (Thompson, 2004):

- precooling to remove field heat and reduce product temperature as quickly as possible after harvest; and
- storage to maintain products at an optimum temperature during accumulation of loads and during transport and distribution to markets.

Reducing temperature decreases product metabolic activity, reduces ethylene production and action, and slows ripening, decay development, wilting and hence rate of deterioration. Different crops can be cooled using different methods (their effectiveness is compared in Table 1). However, for most common greenhouse crops, forced air cooling is probably the most useful and cost-effective.

Precooling

Products should be placed in a cool shaded place as soon as possible after harvest; if left exposed to the sun, product temperature will increase rapidly and deterioration will accelerate. The best practice is to remove field heat as soon as is practicable after harvest or packing; this is generally undertaken in a precooling facility. Precooling can be achieved using several different systems, some preferable for specific products.

TABLE 1

Comparison of typical product effects and relative cost for six common cooling methods

	Room	Forced air	Hydro	Electric evaporative	Passive evaporative	Package ice
Typical cooling time (h)	20–100	1–10	0.1–1.0	20–100	40–100	0.1–0.3
Produce moisture loss (%)	0.1–2.0	0.1–2.0	0.0.5	No data	No data	No data
Water contact with produce	No	No	Yes	No	No	Yes
Potential for decay	Low	Low	High	Low	Low	Low
Capital cost	Low to medium	Low	Low	Low	Low	High
Energy efficiency	Low	Low	High	High	High	Low
Portability	No	Sometimes	Rare	No	Possible	Yes
Limitations and concerns			*	**	**	***

* Recirculated hydrocooled water must be sanitized constantly to minimize buildup of pathogens.

** Evaporative cooling to a few degrees above the ambient wet bulb temperature.

*** Melting ice can cause physical hazards during transport and unloading; packages need to be moisture-proof and therefore tend to be expensive.

Kitinoja and Thompson, 2010

Passive (room) cooling

The most common method, a normal coolstore is used with no special alterations. The product (in various types of containers) is exposed to cold air with a minimum velocity of 60 m/min and cooled by a combination of conductive and evaporative cooling, but the process is slow and not recommended for rapid removal of field heat. Products are cooled and stored in the same coolstore. This system is relatively inefficient compared with others available, but it is ideal for longer-term storage if required.

Forced air (or pressure) cooling

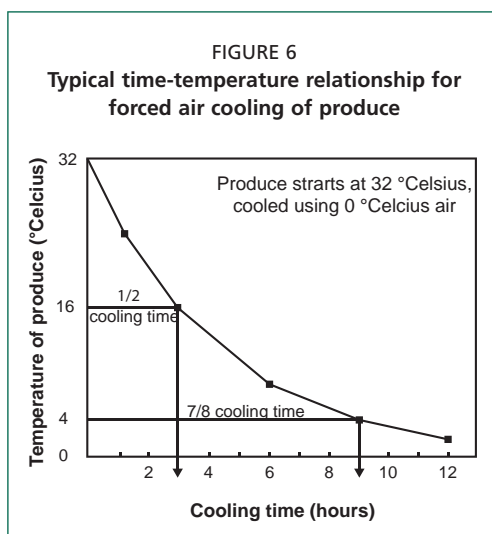
Much faster than normal room cooling, cold air in a coolstore is forced through produce packed in boxes or pallet bins. A number of airflow systems are used, but the tunnel cooler is the most common. Two rows of products in packages or bins or on pallets are stacked on either side of an air-return channel. A tarpaulin or strong plastic sheet is placed over the product and the channel, creating a small difference and thus drawing air through the product. The product is cooled in batches and cooling times range from 1 hour for cut flowers to more than 6–8 hours for larger, solid fruit and vegetables. Temperature reduction is less marked in products packed with airflow-restricting materials such as polyethylene (PE) bags or paper wraps.

Forced air cooling has several advantages over passive cooling:

- The product remains for a shorter time at field or elevated temperatures.
- Cooling times are short and cooling units are efficient.
- Products are cooled in a variety of containers without wetting or excessive handling, provided adequate ventilation openings are present.
- For large volumes requiring cooling, energy-efficiency is increased.

- Available coolstores can be easily converted to forced air cooling with only a small investment in fans, provided that they are of adequate size and cooling capacity is available.

Mobile precooling units have been developed for farmers with small properties and no access to expensive packing facilities. These mobile units vary in size and capacity and can be moved or relocated in different production areas as required. All products cool rapidly at first then more slowly with time. Regardless of the starting temperature of the product, the shape of the product temperature curve remains the same for a given product type; packing density; container type, orientation and ventilation; volume-to-surface ratio of product; airflow capacity and distance travelled by cooling air.



The 7/8 cooling time is an industry standard describing the time required to remove 87.5 percent of the temperature difference between the product starting temperature and the temperature of the cooling air (Figure 6). Cooling should commence as soon as possible after harvest, preferably within one hour. Product temperature should be recorded before and after precooling to ensure system efficiency. The cooling rate is related to three key factors:

- length of time in the precooler sufficient to reach the desired temperature;
- maintenance of constant cooling air temperature; and
- free circulation of cooling air over all product surfaces (containers must have adequate ventilation holes and be correctly aligned on pallets).

Care must be taken to ensure that weight loss is minimized during the cooling process by maintaining relatively high humidity in the cooling room.

Vacuum cooling

This method is suitable for selected leafy crops with a high surface to volume ratio, such as lettuce, spinach, herbs and celery. It is a very fast cooling method that relies on evaporation from throughout the product; the energy for water evaporation is obtained from the field heat of the crop. Approximately 0.2 g of water are lost from every kilogram of product for each 1 °C of cooling; therefore, the product is thoroughly wetted prior to sealing in the vacuum chamber, and the process of pressure reduction is carefully controlled to ensure that the product does not go below its freezing point. For products that lose water easily (e.g. leafy vegetables),

adequate cooling takes 20–30 minutes, even when wrapped in film. Vacuum cooling is common practice in some countries for cooling lettuce; however, the equipment is expensive to purchase and operate, therefore, it is mainly used in large volume systems or in a cooperative manner among several producers.

Hydrocooling

This method uses cold water to remove field heat at a rate faster than forced air cooling, and it does not remove water from the product in the process. It is used for a number of fruit and vegetable crops, including asparagus, peas, beans, cucumbers and courgettes. Hydrocooling is most efficient when individual products are completely covered with cold water, either by total immersion or thorough drenching; the process is less efficient with palletized loads, especially in closed containers. Careful operational management is essential to achieve thorough cooling; this is done by constant monitoring of both water and product temperatures, adjusting the product exposure time as required. Water must be clean (of potable standard) and sanitized (usually with chlorine) to prevent buildup of dirt and pathogenic microbes; it should be changed frequently. Packages used in hydrocooling must allow movement of water across the product while being robust enough to withstand prolonged wetting; plastic or wood containers are quite suitable for hydrocooling.

Ice cooling

Crushed or flaked ice is commonly used to cool leafy crops, broccoli, green onions, sweet corn and musk melons. Melting ice absorbs heat energy and thus cools the product quickly, minimizing moisture loss. Crushed ice or ice slurry is sprayed on top of produce in individual (polystyrene or plastic) or palletized containers before or during transport. While this method of cooling is used commercially, it is not generally recommended because it is unnecessary, expensive and has the potential to increase rot development during storage and transit because of the extended exposure to liquid water as ice melts.

Cooling – GAP recommendations

- Harvest should take place in the early morning hours and not during times of high temperature.
- Harvested products must be removed from direct sunlight, preferably into shade.
- The packhouse should be cooled, or at least with good ventilation.
- Different technologies are available for rapid cooling after harvest.
- Forced air cooling is suitable for many products.
- Hydro- and vacuum cooling are appropriate for some leafy vegetables including lettuce.
- Chilling temperatures are to be avoided.
- Mobile units are available for forced air and hydrocooling systems.

STORAGE CONDITIONS AND TEMPERATURE

All greenhouse crops should be cooled to their recommended temperature as soon as possible after harvest (Table 2). Each crop has a different optimum temperature for maintenance of post-harvest quality and reduction of deterioration rate. In general, relative humidity in cool stores should be over 90 percent to minimize water loss from products. Most vegetable crops have little or only moderate benefits from storage in modified (MA) or controlled atmosphere (CA) conditions (2–5% oxygen and 2–10% carbon dioxide depending on crop – see Table 3). Major

TABLE 2

Recommended storage temperatures for maximum storage life of selected greenhouse crops

Product	Temp. (°C)	RH (%)	Approx. storage life	CA/MA benefit
Beans (green or snap)	4–7	95	7–10 days	Moderate
Capsicum (bell pepper)	7–13	90–95	2–3 weeks	None
Cucumber	10–13	95	7 days	Little/moderate
Eggplant	8–12	90–95	2–3 weeks	Little
Lettuce	0	98–100	2–3 weeks	Reduces browning
Melon ('Cantaloupe' ¾ slip)	2–5	95	15 days	Moderate
Melon ('Honeydew')	7	90–95	3 weeks	Moderate
Watermelon	10–15	90	2–3 weeks	None
Tomato (mature green)	13–21	90–95	1–3 weeks	Moderate
Tomato (firm red)	8–10	90–95	4–7 days	Moderate

Sargent *et al.*, 2007 (adapted)

TABLE 3

Effects of controlled/modified atmosphere storage conditions on selected vegetable crops

Product	Effect	Atmosphere	Benefits
Beans (green or snap)	Yes	2–5% O ₂ : 3–10% CO ₂	Colour retention; reduced coloration of damaged beans
Capsicum (bell pepper)	Minor	3% O ₂ : 5% CO ₂ (better for red than green)	Slight reduction in ripening
Cucumber	Moderate	3–5% O ₂	Delay onset of yellowing and decay
Eggplant	Minor if any	3–5% O ₂	Delay senescence and decay for a few days
Lettuce	Moderate; high for fresh-cut	Intact: 1–3% O ₂ : CO ₂ >2% (may induce brown stain) Fresh-cut: <1% O ₂ : 10% CO ₂	Intact heads: respiration and negative C ₂ H ₄ effects reduced Fresh-cut: controls leaf browning
Melon ('Cantaloupe' ¾ slip)	Moderate	3% O ₂ : 10% CO ₂	Delayed ripening, reduced respiration, inhibition of decay
Melon ('Honeydew')	Moderate	3% O ₂ : 10% CO ₂	Delayed ripening, reduced respiration, inhibition of decay
Watermelon	None	NA	No benefit
Tomato (mature green)	Moderate	3–5% O ₂ : 0–3% CO ₂	Delayed ripening and decay development
Tomato (firm red)	Minor	3–5% O ₂ : 0–3% CO ₂	Slight effect on delayed ripening and decay development

UC Davis, 2011 (adapted)

benefits of CA/MA include reduced senescing-inducing effects of ethylene and a lower respiration rate, minimizing the rate of deterioration.

Chilling injury

With the exception of lettuce, all of the crops considered in this chapter are susceptible to chilling injury (CI). Chilling injury is the manifestation of physiological damage that occurs when certain fruits and vegetables are exposed to low, but not freezing, temperatures that disrupt the normal metabolism, causing damage to cell membranes, eventually visible as a range of visual disorders including: pitting, browning, sunken skin tissue, water-soaked lesions, discoloration, premature and uneven softening, skin russetting, poor and uneven coloration, and ultimately decay by invading normally non-pathogenic fungi.

Development of CI is related to the critical temperature of each product and is a function of both time and temperature. The lower the temperature and the longer the time below a threshold, the faster the development of CI. Therefore products must always be stored at temperatures above the chilling temperature throughout the supply chain. Generally symptoms of chilling injury only appear following removal to ambient temperatures (Plate 5).

COOLSTORE DESIGN

Experienced professional engineering companies with extensive experience in fruit storage systems should be used to design and erect coolstores for greenhouse crops that are highly perishable and subject to chilling injury. Too often, companies involved in building cooling systems in commercial buildings or for coldstores for frozen (dead) products are used, with potentially serious negative consequences for products that only require chilling temperatures above 0 °C or between 5 and 14 °C.



Plate 5

Chilling injury symptoms on selected greenhouse grown crops
 Top row: capsicum (green peppers); green (snap) beans; cucumber
 Bottom row: tomato; 'Honeydew' melon; aubergine (eggplant)

Coolstores should be purpose-built for specific operations. Size and capacity depend on volume and product type. Provisions should be made at the design stage to create an energy-efficient system using available technologies. Only approved refrigerants should be used. Coolstores should be constructed on a concrete base (preferably insulated), using prefabricated insulated panels, with a water vapour barrier included in the floor and walls to prevent inward and outward movement of moisture. For controlled atmospheres, rooms must be designed to be gas-tight with appropriate automatic pressure relief valves to compensate for atmospheric pressure changes. Doors must also be insulated, close fitting, and with a plastic or air curtain to minimize air movement in and out during loading and unloading.

Refrigeration systems must be able to cope with predetermined peak loadings and also with any precooling loads that may be imposed on the system. Positioning and capacity of the fans and evaporators is critically important to ensure that airflow within a fully loaded room is adequate to reduce and maintain product temperatures. It is highly recommended that coolstore design criteria:

- ensure that appropriate refrigeration capacity is available for any rooms that will be used for forced air cooling;
- specify requirements for high relative humidity conditions (> 90%) needed for perishable greenhouse products (modern evaporator design enables such high relative humidity to be maintained during operation);
- allow even airflow through packed products when cool rooms are full; and
- include systems enabling fluent and efficient stacking of pallets and movement of forklifts within stores.

All coolstores must be monitored using sensors linked to computer systems with automatic alarm and communication links to the coolstore manager for eventual problems. Temperatures should be monitored continuously at several points within the cool room. Both return and delivery air from each evaporator, as well as temperatures from several locations within the room, must be recorded, as should flesh temperatures of products located in different parts of the storage room. Simply relying on a wall-sited temperature gauge outside the room is totally inappropriate for monitoring product or air temperatures.

Increasingly, coolstores are fitted with radio frequency identification (RFID) units to track the location and movement of fruit placed in the cool room. This facilitates operation, ensures that pallets of products with certain attributes (e.g. size, colour) required for specific markets can be located and removed without delay (generally on a first in, first out basis). Cool rooms should open into a temperature-controlled plenum in which pallets can be accumulated and stored for short periods prior to loading into refrigerated trucks/containers. Products should be loaded directly from the docking bay in the plenum onto the truck to maintain product temperature and to reduce hot air ingress into the truck and plenum (Plate 6).

**Plate 6**

*Refrigerated truck container being loaded at ramp with direct link between refrigerated plenum and truck (left); schematic of airflow in a top air delivery container (right)
Bottom air delivery is regarded as being more effective than top air delivery.*

Coolstore – GAP recommendations

- Coolstores should be located at the end of the packing shed to suit product flow and facilitate loading onto transporters.
- Coolstores should have insulated concrete floors and walls.
- Temperature monitoring of both air and product should be undertaken in several locations in each coolstore to ensure that minimum and maximum checkpoints are not exceeded.
- Computer-controlled monitoring should be used, including automatic alarm to operator in case of emergencies
- High relative humidity can be achieved by minimizing temperature drop with evaporators.
- Only approved refrigerants may be used.
- Temperatures that may induce chilling injury must be avoided.
- RFID systems should be used where possible to manage inward and outward flow of inventory: first in, first out.
- Use only electric forklifts in packhouses and coolstores to avoid ethylene contamination.

MINIMIZING MOISTURE LOSS FROM PRODUCTS

As vegetable products comprise 90–95 percent water, and this content constitutes most of the saleable value, it is essential to adopt protocols to reduce post-harvest water loss to a minimum. Retention of moisture is very important for maintaining quality attributes, including texture, firmness and crispness. Once harvested, any water lost by the product through evaporation cannot be replaced by the plant root and stem system and therefore net water loss occurs mainly via evaporation through stomata on the leaves and lenticels on the fruit. Rupture of the product surface, caused by physical handling damage, also exacerbates water loss. The rate of water loss is dependent on the relative humidity (RH) of the surrounding air; low RH will cause more water to be lost than high RH.

Post-harvest moisture loss during storage can be minimized when the refrigeration system is designed in an appropriate manner. Minimizing the temperature difference across evaporators can result in relatively high RH within coolstores. In addition moisture loss is reduced when products are packed in containers lined with polymeric films.

ETHYLENE

Ethylene is a naturally occurring gas produced by all living organisms and it is both beneficial and detrimental to plants. Ethylene is particularly important in horticulture: on the positive side, it induces and modulates ripening in many crops; from a negative perspective, it induces premature ripening, stimulates senescence and speeds up post-harvest product deterioration.

Fruit may be climacteric or non-climacteric. Climacteric fruit are those where a sharp increase in ethylene production occurs at the onset of ripening, a process which is thought to control initiation of changes in colour, aroma, taste, flavour, firmness, texture and other physiological processes, including the production of more ethylene. Climacteric fruit will ripen after harvest. In contrast, ripening of non-climacteric fruit occurs largely via an ethylene-independent process, the nature of which is currently under intense research. Non-climacteric fruit are ripe and ready to eat at harvest. Climacteric fruit are variously sensitive to exogenous ethylene in the preclimacteric stage, and can produce large amounts of ethylene during ripening.

Ethylene also comes from human-induced sources, in particular pollution caused by fuels burning in internal combustion engines (tractors, trucks, engine-driven forklifts), as well as decaying and senescing vegetation and plant products. Contamination of greenhouses by combustion products from gas-fired heaters has been known to induce abscission of flowers and fruit within the house; electric forklifts must be used in packhouses and coolstores to avoid contamination with ethylene produced by petrol-driven forklifts.

Ethylene can have negative affects at very low concentrations. In some fruit a concentration of < 0.03 ppm is enough to initiate premature senescence. Table 4 shows that production of, and sensitivity to exogenous ethylene varies depending on product type and cultivar of the same genus.

Ethylene is used to ripen tomatoes. Fruit harvested at mature green can be ripened by exposure to 100 ppm ethylene at 13–20 °C for 24–72 hours. Air circulation must ensure that temperature uniformity is achieved with specially designed ripening rooms. Such treatments can facilitate managed marketing. Ethylene appears to have no effect on ripening of capsicum.

TABLE 4

Production, sensitivity and symptoms following exposure of selected greenhouse crops to ethylene

Product	Ethylene production ^a	Ethylene sensitivity	Climacteric	Symptoms
Beans (green or snap)	0.05	Moderate	No	Yellowing, browning
Capsicum (bell pepper)	0.1–0.2	Low	No	Slight reddening
Cucumber	0.1–1.0	High (1–5 ppm)	No	Yellowing and decay
Eggplant	0.1–0.7	Moderate to high (>1 ppm)	No	Calyx abscission
Lettuce	0.2	High	No	Browning on midrib
Melon ('Cantaloupe' ¾ slip)	40–80	Moderate	Yes	Premature ripening
Melon ('Honeydew')	0.5–10	Moderate	No	Softening
Watermelon	0.1–1.0	Moderate	No	Softening
Tomato (mature green)	4.3–4.9	High	Yes	Initiates ripening
Tomato (firm red)	4.3–4.9	Moderate	Yes	Initiates ripening

^a Ethylene production rates are $\mu\text{l/kg.h}$ at 20 °C.
UC Davis, 2011 (adapted)

1-Methylcyclopropene [MCP]

A major advance in reducing the action of ethylene has been in the use of 1-methylcyclopropene (1-MCP; SmartfreshSM). This chemical, that works as a gas released in a controlled manner into airtight storage rooms, has been approved for use on several fruit crops in a number of countries. It inhibits ethylene action and in doing so prevents autocatalytic ethylene biosynthesis. SmartfreshSM is approved for use in some countries on tomatoes and melons. For tomato, post-harvest application of 0.5–1.0 μl per litre 1-MCP for 24 hours delayed or inhibited quality deterioration and extended shelf-life of several tomato cultivars whilst maintaining organoleptic quality. Similarly SmartFreshSM is registered for use on melons in some countries and can be used to slow down senescence and maintain quality during extended storage.

New formulations of 1-MCP (including HarvistaTM) are being developed for use as pre-harvest sprays for horticultural crops, but are generally not yet available for commercial use. SmartFreshSM is registered in some countries for use on vegetables and herbs (tomato, broccoli, cucumber, carrot, lettuce, paprika, capsicum and squash). Its main effect is to decrease the rate of ethylene-induced senescence, resulting in: reduced yellowing of leaves (beans and broccoli), fewer disorders (browning and russet spotting of lettuce), extended shelf-life (cucumber), reduction in softening and delay in colour change (tomato), and reduced shatter with abscissions (bunched cherry tomato).

Treatments to reduce deleterious effects of ethylene

A number of practices can reduce the negative effects of exposure to ethylene:

- Avoid exposure to environmental pollution with varying amounts of ethylene (e.g. do not locate packing houses or coolstores downwind of busy roads).

- Avoid physical, physiological and pathogen damage to products during harvesting, handling, packing, storage and transport; physically damaged or decaying goods produce ethylene.
- Remove all reject products from packhouses and coolstores.
- Use electric forklifts in packhouses and coolstores, as internal combustion engines burning petrol, diesel or gas produce ethylene.
- If necessary, use ethylene scrubbers (e.g. potassium permanganate or activated charcoal) in coolstores to reduce ethylene concentrations.
- Ensure that coolstores run efficiently, maintaining recommended temperatures that will minimize ethylene production by products.
- If permitted and required, treat with SmartFreshSM.
- Use long-life cultivars, if available, with reduced susceptibility to ethylene; this is possible with tomatoes.

Management tools available to minimize exposure of products to ethylene

- Locate growing facilities, packhouse and coolstore upwind of major roads or pollution sources from which ethylene may flow.
- Situate truck loading facilities on the downwind side of packing and storage facilities.
- Use electric forklifts in and around such facilities.
- Prohibit smoking in and around the facilities.
- Instantly remove any senescent or rotting product from the site.
- Within coolstores, use activated charcoal or other scrubbers that remove ethylene from the air stream; they can be incorporated into the store design.
- If registered, use 1-MCP as a means of preventing ethylene action.

SORTING AND GRADING

After harvest, fruit has to be sorted and graded to meet specific quality, market and export phytosanitary standards. Growers and all staff involved in the operation must be aware of specific market requirements.

The packhouse and associated coolstore(s) should be near to but separate from the greenhouse. They should be sited far from or downwind of main roads to minimize exposure to ethylene pollution from internal combustion engines. A covered area for receiving and accumulating produce is essential for protection from exposure to direct sunlight. All reject products should be removed from the packhouse as they are a potential source of post-harvest pathogen inoculum and subsequent ethylene production. In countries with high ambient temperatures, packhouses should have a cooling system both for the comfort of staff and to reduce the tendency of produce to heat post-harvest.

To enhance efficiency, a packhouse must be well designed to facilitate flow from the harvested product at one end through to coolstores and loading outlets at the other. There must be adequate space to contain packing line(s) (with room for future expansion) for washing, sizing, sorting, segregating, sanitizing, waxing, packing and accumulation of produce. Space must be made available for (temporary) storage of excess products out of the sun, as well as conveyors, packing materials, labels and pallets. In addition, a centralized computer control room should be in a central and elevated position so that operators can view all aspects of the system easily. A separate space is required for the quality assurance team, an integral part of any modern packing and marketing operation. In some large operations it may be desirable to have a laboratory where physical and chemical analyses can be undertaken.

During unloading, care must be taken to avoid causing mechanical damage. Products are taken from the containers into which the crop was harvested in the greenhouse, and placed on sorting tables where products can be segregated according to a range of attributes as specified for selected markets. As consumers become increasingly demanding in terms of the quality of produce that they purchase, uniformity and quality in the product lines are expected.

There are many different types of grading and sizing systems available today. The choice of which system to use depends on the product, the volume to be handled, and the degree of segregation required, which in turn depends on the number and type of markets supplied. Such systems can range from simple hand sorting and packing to highly sophisticated computer controlled integrated systems with minimal labour requirements. Where computer controlled systems are not used, lighting and ergonomic design must be optimal for the most labour-intensive part of the sorting and packing operations. Staff must be able to view each product unit as it passes along the sorting table situated at a height that minimizes reaching and lifting. Space must be provided for stools, and ear protection for staff to minimize noise fatigue.

Good agricultural practice management should ensure that the speed of produce movement is appropriate for the quality level of any line: the more variable the product quality, the slower the line. Adjustment of the bin dump rate is an efficient way of ensuring optimum efficiency and accuracy of sorting at a rate consistent with the overall quality of each product line. Sorting and segregating staff must be well trained, and consistency of quality for minimum acceptability and criteria for rejection agreed and implemented by all team members. Staff should have specific responsibilities, with experienced workers located downstream of less experienced workers. Staff rotation is important to avoid tiredness and reduced worker efficiency. Computer-controlled sorting systems can segregate for weight, colour, blemish, diameter, shape, density and internal taste.

Current models comprise fully integrated systems comprising: sophisticated size and segregating control systems, peripheral bin dumps, water flumes, a range of packing options, labelling facilities with full traceability capability, and automatic pallet stacking and wrapping. High speed cameras and near infrared spectroscopy systems are used operating at speeds of 12–15 fruit per second on a single lane. Modern packing lines are reasonably well designed to minimize both number and extent of drops at points of transfer or direction change. However it is essential to undertake regular inspections and ensure that all surfaces at such drops or transfer points are well padded with energy-absorbent material to reduce mechanical damage.

POST-HARVEST PATHOGENS AND DECAY

All fresh vegetables are very perishable and susceptible to infection by a number of post-harvest pathogens. Although most products are resistant to most pathogens, certain specialized pathogens cause substantial financial losses. Infection occurs when the spores of fungi or bacteria grow on and penetrate wounded or stressed tissue. Most losses are caused by organisms infecting produce that has:

- been under stress during the growing season;
- suffered physical damage during harvest and handling;
- been stored too long after harvest; or
- sustained chilling injury.

It is very important to ensure that any chemicals applied pre- or post-harvest to eradicate or prevent infection, are applied according to the manufacturer's instructions in order to prevent buildup of residues above the accepted minimum threshold levels. Such chemicals must be registered for use in both the country of production and the country where the product is to be marketed. Physical damage creates avenues through which it is possible for fungal and bacterial pathogens to enter the fruit and cause infection resulting in serious economic losses (Plates 7, 8 and 9). In some cases physiological disorders (e.g. blossom end rot) can lead to infection.

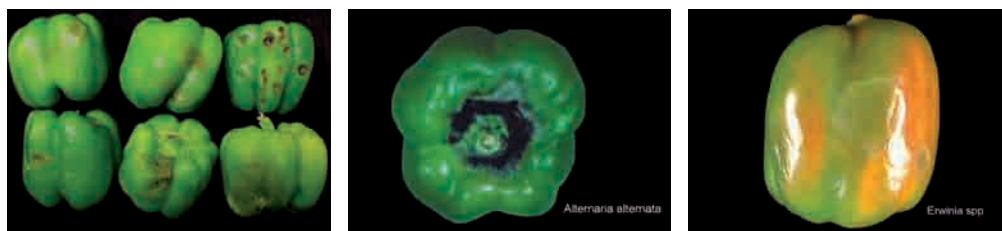


Plate 7

Capsicum – physical damage through which decay micro-organisms can enter and infect tissue (left); *Alternaria alternata* (middle); bacterial rot (right)

**Plate 8**

Tomato – blossom end rot, a pre-harvest disorder caused by calcium deficiency and water stress (left); Rhizopus stolonifera – infected through damaged tissue (middle); Fusarium rot (right)

**Plate 9**

Bean – anthracnose caused by Colletotrichum sp. (left); bean grey mould caused by Botrytis sp (centre); cucumber with Fusarium rot (right)

Minimizing post-harvest decay – GAP recommendations

- Maintain good sanitation in the growing area, at harvest and throughout the supply chain.
- Ensure that all equipment is kept clean and sanitized regularly.
- Prevent physical damage from occurring throughout the chain from harvest to retailer.
- Ensure removal from packing house and coolstore of senescing and decaying products and vegetation.
- Use appropriate and permissible chemicals to eradicate or suppress growth of pathogens.
- Remove field heat and achieve recommended storage temperature as soon as possible after harvest; store and transport products at lowest recommended temperatures, but above critical threshold temperatures that can induce chilling injury.
- Avoid storing wet produce and wetting product surfaces; create RH conditions to minimize water loss.
- Use CA or MA storage where applicable and economically viable to do so.

SANITATION AND FOOD SAFETY

Today's consumers are preoccupied with food safety. Quality assurance systems exist to ensure food safety: a factor critical for sustained marketing success. It is imperative that measures are implemented to minimize the risk of contamination from human pathogens and reduce the risk of post-harvest decay from fungal and bacterial pathogens. Appropriate phytosanitary processes must be implemented in all post-harvest facilities and operations, and approved by appropriate auditors as required by local, national and marketing authorities. Sanitation is generally regarded as an integral part of any hazard analysis and critical control point (HACCP) system applied in the greenhouse, packing house, grading machinery, coolstores, transport vehicles, distribution centres and markets. A number of sanitizing agents are approved for use on fresh products, but must be approved by local authorities and the market (Table 5).

New systems are becoming available that involve strict monitoring and control of the cool chain (from packhouse to market). They are used for an increasing range of horticultural products in intercontinental sea freight. In one system, controlled release and monitoring of ozone is used to reduce pathogens and to minimize ethylene action, thus reducing the rate of deterioration, enhancing quality at wholesale and retail markets, and increasing profitability for all those in the supply chain.

TABLE 5
Sanitizing chemicals for post-harvest use in packhouses and coolstores

Compound	Advantages	Disadvantages
Chlorine ^a	Relatively cheap Broad spectrum – effective on many different microbes	Corrosive to equipment Sensitive to pH <6.5 or >7.5 – activity reduced and noxious odours increased
Chlorine dioxide	Activity much less than chlorine	Must be generated on site Greater human exposure risk than chlorine Off-gassing of noxious gases common Concentrated gases potentially explosive
Peroxyacetic acid	No known toxic residues or by-products Produces very little off-gassing Low corrosiveness to equipment	Activity reduced in presence of metal ions Concentrated product very toxic to humans Sensitive to pH – generally reduced activity with pH > 7–8
Ozone	Very strong oxidizer/sanitizer Can reduce pesticide residues in water Less sensitive to pH than chlorine (but breaks down must faster when pH >8.5) No known toxic residues or by-products	Must be generated on site Ozone gas toxic to humans – off-gassing can be a problem Treated water should be filtered to remove particulates and organic matter Very corrosive to equipment (incl. rubber and some plastics) Highly unstable in water (half-life 10–15 minutes); may be <1 minute in water with organic matter and soil

^a Most widely used sanitizer for packing house water systems.

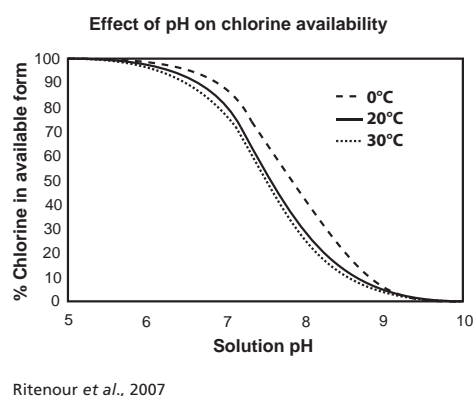
Although quaternary ammonia is an effective sanitizer with useful properties and can be used to sanitize equipment, it is not registered in the United States for contact with food.

Sargent *et al.*, 2007

Cleaning and sanitation – GAP recommendations

- Clean produce with potable water or treat with 100–200 ppm of free (available) chlorine at a pH of 6.8–7.2 in recirculating water; this can be done by dipping, drenching or spraying.
- Provide chlorine as sodium hypochlorite, calcium hypochlorite or liquid chlorine; other chemicals that may be used under specific conditions include chlorine gas, chlorine dioxide gas and ozone, but these can be toxic to humans and need handling with great care (Table 5).
- Maintain pH at 6.8–7.2: pH > 8.0 is less effective and pH < 6.5 becomes too corrosive for equipment and product (Figure 7).
- Adopt appropriate methods (automated/manual) to regularly and accurately measure free chlorine concentrations and pH of water.
- Maintain water temperature of the chlorinated solution at ~5 °C above pulp temperature of product.
- Change recirculating water daily but ensure that environmental guidelines are followed for disposal of this water.
- Remove surplus surface moisture by vibration or airflow.

FIGURE 7
Chlorine availability in aqueous solutions at different pHs and water temperatures



QUALITY AND MARKET STANDARDS

Individual countries are likely to have their own domestic quality or marketing standards for fruit and vegetables and these may vary from one country to another. It is important that producers understand and adhere to these standards. Apart from the general guidelines outlined by the Codex Alimentarius Commission, export destinations have specific requirements for food quality and safety that must be met by suppliers. Entry to export markets may be refused if such quality and safety standards are not met.

The European Union (EU) has specific and wide-ranging quality and marketing regulations. For example, Marketing Standards for Fruit and Vegetables Commission Regulation (EU) No. 543/2011¹ builds on Council Regulation (EC) No. 1234/2007 that states that “all fruit and vegetables should comply with the general marketing standard (sound, fair and marketable quality) and indicate the country of origin. The latter must be in a language understandable by the

¹ Available at: http://www.freshquality.eu/php/document.php?catdoc_id=49.

consumer of the country of destination. This standard shall apply in all marketing stages including import and export, unless stated otherwise. The holder of these products may not display or market them in any manner than in conformity with the standard. The holder is responsible for ensuring this conformity.”

Commission Regulation (EC) No. 543/2011 maintains specific marketing standards for ten products (including lettuces, sweet peppers and tomatoes). An interpretative guide of each of these standards for a wide range of fruit and vegetables is available in the product specific section of the Fresh Quality Guide.²

There is a growing demand among consumers in both local and export markets for products that are actually or perceived to be of enhanced quality. Consumers want products that are free of visual defects, visually attractive, tasty with pleasing texture, free of contaminants and preferably endowed with health benefits. Proverbs such as “An apple a day keeps the doctor away” have strong roots in traditional health cures used by our ancestors. Moreover, an increasing number of consumers want products obtained from environmentally friendly, sustainable and ethical production and post-harvest systems. The market niche for organically produced fruit and vegetables, while still modest, has increased in recent years, although it is mainly limited to consumers with higher incomes, since these products are often sold at a higher prices. Some consumers expect products to originate from specific geographic areas that have soil, climate and cultural characteristics that contribute to a unique product flavour and quality. For growers who are market-oriented and keen to differentiate their products based on the region in which they are grown, developing the capacity to meet high quality standards while following such trends can represent a major challenge. European texts containing guidelines for labelling products “Protected Geographical Indication” (CE No. 510/2006) or “organic” (CE No. 889/2008) are essential reading for growers wishing to target these market sectors.

All growers strive to gain and increase market acceptance and market share, achieved by the consistent production of high quality products over several years. Buyers become aware of quality growers and seek to purchase their products at premium prices. To enhance their position, growers should therefore create a brand or label identifying them to the market and guarantee continued supply in terms of quantity and quality to maintain their reputation. Labels and brands should be created to establish production location and details of product size, and a barcode should contain this information with traceability. Recent developments with the quick response (QR) code are likely to have impacts in product advertising and marketing. The QR code is a cell phone readable barcode that can store Web site URLs, plain text, phone numbers, email addresses and other alphanumeric data (Figure 8). This technology has become a focus of advertising strategy, since

² Available at: http://www.freshquality.eu/php/category.php?cat_id=115.

FIGURE 8
A QR code – an increasingly important technology for providing relevant grower and product information for consumers, readable by mobile phone



in the GLOBALG.A.P. manifest. GLOBALG.A.P. is a private sector organization that has established voluntary standards for certifying production processes of agricultural and horticultural products internationally. It provides a practical manual for good agricultural practices anywhere in the world (<http://www.globalgap.org>).³

QUALITY CONTROL PROCESSES

With increased globalization of trade, and the associated movement of fresh vegetables across national borders, it is critically important that growers recognize and adhere to both phytosanitary and quality standards in different countries and markets. In general, government action is limited to ensuring pest and disease status of produce destined for export, responsible for providing inspection services and issuing the phytosanitary certificates required by importing countries. Grade and quality standards are likely to vary between countries, markets and supermarket chains, the latter setting their own quality standards, although adherence to GLOBALG.A.P. standards is almost universally required apart from in unregulated local markets. In addition, statutory (Codex Alimentarius) standards must be attained and maintained and the EU has basic quality requirements that must be met.

The Codex Alimentarius Commission was created in 1963 by FAO and WHO to develop food standards, guidelines and related texts such as codes of practice under the Joint FAO/WHO Food Standards Programme. The main purposes of this Programme are protecting health of the consumers and ensuring fair trade practices in the food trade, and promoting coordination of all food standards work undertaken by international governmental and non-governmental organizations.

http://www.codexalimentarius.net/web/index_en.jsp

it gives consumers quick and effortless access to the brand or grower Web site that contains pertinent information about both the grower and the production site.

GLOBALG.A.P. REQUIREMENTS FOR FOOD SAFETY

In response to widespread consumer demand, major supermarket chains around the world require growers to provide food that is safe to eat, produced in an environmentally responsible and sustainable manner. While different supermarkets have established different systems, they can all be satisfied if growers and produce handlers use the well-established protocols outlined

in the GLOBALG.A.P. manifest. GLOBALG.A.P. is a private sector organization that has established voluntary standards for certifying production processes of agricultural and horticultural products internationally. It provides a practical manual for good agricultural practices anywhere in the world (<http://www.globalgap.org>).³

Well-trained staff should be dedicated to quality control, working to agreed schedules

³ See chapter 21.

and quality sampling protocols determined by the grower organization to meet specific market and customer requirements. It may be desirable to establish laboratory facilities to monitor: grade standards; quality attributes (including weight, size, colour and freedom from defects); and, as necessary, other intrinsic quality attributes (e.g. dry matter, sugar content and acidity). Residue analysis must be done in a registered/licensed laboratory.

PACKAGING

Packaging is required to get the product from the production centre to the consumer in the market place. It serves three purposes:

- Protection from physical, physiological and pathological damage during handling, storage, distribution and marketing.
- Assembly of products in uniform quantities for ease of handling and transport (producing units, such as palletization, may be adopted).
- Presentation with containers labelled with a distinctive brand/logo for promotion, information about the grower and specific product traceability including harvest and/or packing date (many containers are specially designed to be the final presentation display in the supermarket and thus contain attractive designs and brands, as well as barcodes indicating prices).

Containers may be of many types and materials but must always meet the needs of the buyer and customer (buyers for large supermarkets often condition the type of container used). Furthermore, society is concerned about sustainability and environmental issues and dictates that containers and packages must be recyclable or returnable. At the same time packages must be designed to allow adequate ventilation during cooling and storage as well as being strong enough to withstand the rigours of multiple handlings along the supply chain. A container must be constructed of a material strong enough that the package, and not the product, bears the weight of a stacked pallet, and will not weaken if the pallet gets wet in transit (Plate 10). In general, large retail chains have attempted to standardize package size and shape to reduce waste and associated costs. In some countries, this had led to adoption of fibreboard trays and reusable plastic crates or trays having a “standard footprint” that fully utilizes the standard pallet (Plate 11).



Plate 10

Examples of different types and sizes of plastic returnable crates

**Plate 11**

Examples of different types of packaging used for tomatoes, capsicums and cucumbers

Package dimensions are becoming important internationally and size or shape are chosen to increase efficiency in packing, handling and storage; an optimal length-to-width ratio is about 1.5 : 1. International recommendations indicate that maximum pack weights should be about 15–20 kg, able to be moved easily by individuals of both genders, but with many “retail ready” products (retail packs of 2–5 kg single layers are becoming increasingly popular).

Unitization refers to the assembling of packages and containers onto pallets; this enhances efficiency in the distribution chain as it enables relatively large numbers of individual containers to be handled mechanically as one unit with appropriate equipment. Attempts have been made internationally to adopt standardized cartons, pallets and shipping containers for fresh produce to optimize stowage efficiency in transport containers. An important characteristic of any package or container is that it must allow rapid and unimpeded air ventilation during cooling and storage; with fibreboard boxes or crates, it is essential to have adequate holes for ventilation while retaining adequate mechanical strength to withstand the weight of all containers on a pallet. Polymeric films, either perforated or not, depending on permeability and the product, can be used with perishable vegetable crops to minimize water loss and, if required, to create modified atmospheres that may slow the deterioration rate.

Automation of packing systems is increasingly popular in larger facilities: it reduces labour needs and costs, enhances uniformity and consistency of product sorting, and can if necessary operate 23 hours per day (1 hour set aside for maintenance). Potential exists for entire packing lines to be automated, and several international companies provide appropriate equipment to this end for crops such as tomatoes.

For most crops it is sensible to strap and wrap pallets to provide stability during transport and distribution to and within markets. In some cases pallets are

shrink-wrapped in polymeric films, but this is not recommended where ventilation through the pallet and over the product is required to minimize respiration rate and ethylene production during storage, transport and distribution.

TRACEABILITY

Logistics systems are in a period of major change, moving from tracking capabilities to tracing throughout the entire supply chain from producer to supermarket.

- Tracking is the capacity to follow the path of a specific item through the supply chain as it moves within and between organizations.
- Tracing is the capacity to identify the origin of a particular item or batch of produce located at any place and at any time within the supply chain from records held upstream of the original production and packing source.

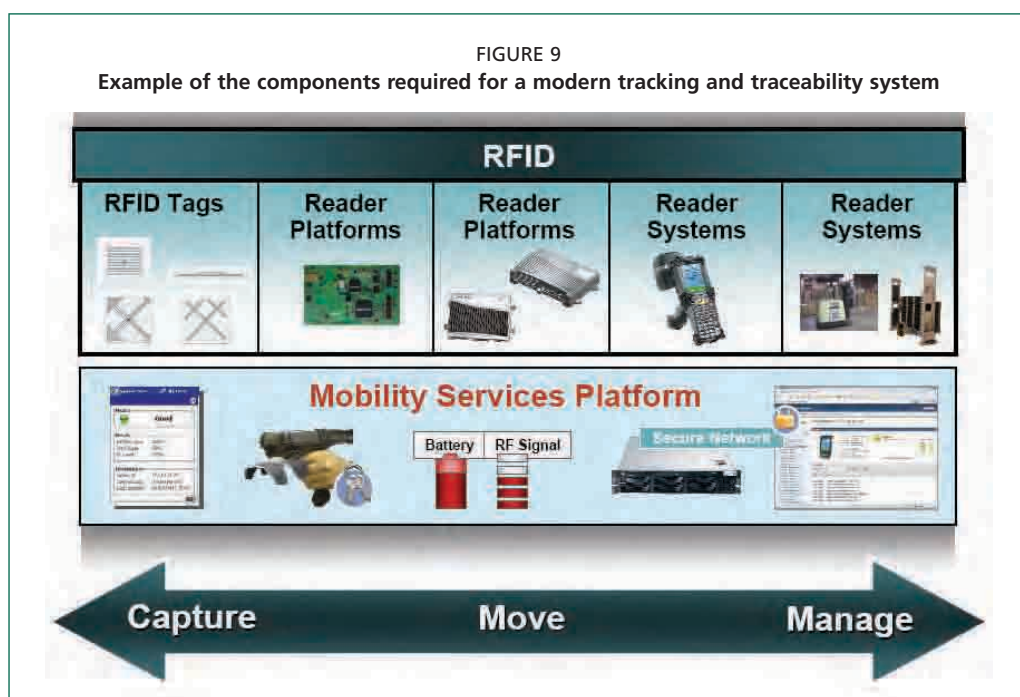
Tracking serves both to get goods to market and to establish that the item reaches the customer on time. Tracing is difficult for most organizations to implement, and complete and verifiable traceability often represents a major challenge. But traceability is the key to risk management, and is increasingly becoming a requirement of modern trade for reasons of biosecurity, food safety, physical security, and brand and market protection.

Traceability is an increasingly important commercial issue because of the convergence of five forces:

- consumer preferences
- retailer profits
- wholesaler profits
- demands for safety and biosecurity from the health and agriculture authorities
- requirements for traceability of the product to its point of origin or contamination (requirements made also by health and agriculture authorities)

New technologies offer cost-effective, value-creating traceability solutions:

- Electronic product code identification (EPC) and other radio frequency identification (RFID, Figure 9) systems introduced into global logistics chains, spearheaded by Walmart and Tesco among others – these initiatives are designed to secure significant productivity gains and provide customer safety and quality assurance.
- More secure logistics systems following security upgrades in the wake of terrorist activity in many countries.
- Emerging technologies that assist in traceability and authentication of products and their points of origin. An increasing number of recently developed commercial technologies are in this category as they become cheaper, more precise and accessible; they counteract the rising incidence and business impact of counterfeiting activities within global trade, and the



increasing access of counterfeit producers to modern production technologies with the globalization of industrial activities.

Some existing commercial systems are available and being used for horticulture. One such system uses relatively cheap disposable sensors (located in individual cartons, if necessary) and provides:

- continuous quality monitoring without human intervention;
- real-time alerts so that corrective or compensative action can be taken before it is too late;
- on-the-spot quality reports for informed decision-making;
- complete supply chain traceability: in the warehouse, in transit and during post-arrival storage; and
- continuous communication with the central control centre.

As technology advances, sensors and information systems will be able to handle ever larger amounts of information from an increasing number of environmental signals. RFID components are becoming smaller and more powerful (Plate 12, Figure 9) and small sensors are becoming commercially available that will measure CO₂, O₂ and ethylene as well as product pulp temperature within loads on a continuous basis. Some companies offer services to install systems that will generate information along international supply chains and claim to have significantly reduced post-harvest losses (and hence increased profits) by ensuring that storage conditions along the entire chain are optimized.

RFIDs have a number of beneficial uses in addition to traceability; these include inventory management, labour-saving costs, security, and promotion of quality and safety. Barcodes and labels must include all relevant information about the product as required by specific markets. However, as technology develops, it is possible to envisage the inclusion of information (e.g. photographs) about the producer, family and farm as well as attitudes towards sustainability, establishing a closer link between the end consumer and the producer – an invaluable marketing tool.

TRANSPORT TO MARKET

To maintain product quality through the post-harvest cool chain, palletized loads should be transported from coolstores to markets in refrigerated containers. If optimum temperatures are attained during storage, then short transit journeys from packhouse to market could be undertaken by non-refrigerated “cooltainers” or canvas-sided trucks, but use would be dictated by distance from market, perishability of product and ambient temperatures. For longer journeys to distant markets, it is preferable to use refrigerated containers on planes, trucks or ships, to ensure that storage temperatures are maintained from packhouse to warehouse and beyond. Trucks should preferably have air suspension to reduce vibration damage during transit to the market.

Normally products are loaded into pre-cooled 20- or 40-foot reefer containers at the coolstore, preferably from a temperature-controlled plenum between the coolstore and the truck. Pallets are loaded so that maximum airflow can pass uniformly through the pallets to maintain optimum storage temperature during transport to the market.

SUPPLY CHAIN

The basic considerations and recommendations for maintaining post-harvest quality are similar, regardless of product, location or nature of the distribution system. However, differences in detail will occur in the technologies employed and between products from different production sites depending on the distance from and nature of particular market destinations. Handling, storage and distribution recommendations depend on the time period between the production site and the

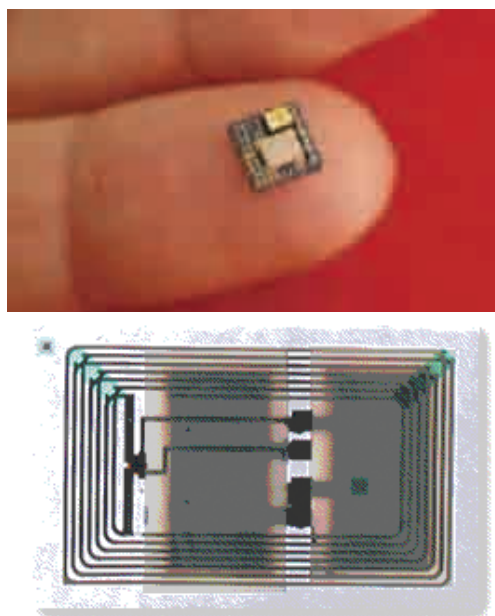


Plate 12

Examples of miniaturized radio receivers that are used in RFIDs (some specific nanosensors have now been developed especially in relation to monitoring food safety)

Maintaining the cold chain for perishables

Harvest

- Protect product from the sun
- Transport quickly to packing house

Cooling

- Minimize delays before cooling
- Cool product thoroughly as soon as possible

Temporary storage

- Store product at optimum temperature
- Practise first-in-first-out rotation
- Ship to market as soon as possible

Transport to market

- Use refrigerated loading area
- Cool truck before loading
- Load pallets towards centre of truck
- Put insulating plastic strips inside door of reefer if truck needs to make multiple stops
- Avoid delays during transport
- Monitor product temperature during transport

Handling at destination

- Use refrigerated unloading area
- Measure product temperature
- Move product quickly to proper storage area
- Transport to retail markets or food service operations in refrigerated trucks

Handling at home or food service outlet

- Display product at proper temperature range
- Store product at proper temperature
- Use product as soon as possible

Kader, 2006 (adapted)

consumers, as well as the ultimate intended use (fresh, processed or fresh-cut).

In many countries technologies have been introduced to improve efficiency in the face of rising costs or shortages of labour, materials and energy (not always the case where labour is readily available). Increasingly sophisticated and mandatory quality requirements imposed by international supermarket chains mean that there is a demand for products that are uniform and consistently free from physical, physiological or pathological defects; modern equipment can ensure that only quality products are packed and distributed down the supply chain to consumers.

The process of getting products from the farm to the consumer used to be a series of discrete steps organized by independent and unrelated operators; each step had its own cost and the grower received the residue once all costs had been covered. Growers generally received an ever smaller proportion of the final market price as supermarkets increased quality and safety demands. The international horticultural industry is changing: the past decade has seen the development of holistic systems with integration and communication among all firms operating in the supply chain; mutual benefits accrue based on cooperation and sharing of vital information on all aspects of the transactions.

The critical steps along the cool chain section of the supply chain (from farm to consumer), are identified on the left. A very important element of a successful, vertically integrated supply chain is feedback from and between all steps along the chain. Modern technology allows instantaneous worldwide communication 24 hours a day

for 365 days of the year. Perishables quality monitoring systems available from several commercial companies provide information in transit. The marketing sector must rapidly provide feedback to suppliers and other supply chain partners, to ensure that quality or market issues can be addressed and sensible decisions made on the basis of supply and demand. This can be done by mobile phone, email or fax, and such information must be accurate, timely and of value to the producer.

EDUCATION AND TRAINING OF STAFF

Loyal well-trained staff are essential for a successful business. The people who work in post-harvest facilities are more important than the sophistication of the equipment; without well-trained personnel, efficient and sustained operation may be compromised. It is important to ensure that all staff understand the nature of the product being grown, the reasons for the diverse management decisions that have to be made at critical times and the consequences of production and post-harvest mistakes on final profitability of the business. It is strongly suggested that managers establish regular opportunities for staff to update skills and knowledge. Provision of a fair, equitable and friendly working environment is as important as paying good wages if staff are to work in the best interests of the operation. The more they are informed of the enterprise, the more they will consider themselves an integral part of a successful business.

GAPs for harvest and post-harvest management

Profitability is the key driver for greenhouse production of high quality products to meet market demand when supply is lowest and economic returns are greatest.

Consumer needs and requirements must be satisfied: consumers make the final decision about product quality; repeat purchases are the key to ongoing commercial success and sustained profitability.

Supply chain perspective must be adopted by growers: all links in the chain are critical to sustained success and profitability. Vertical integration, collaboration, and communication among all firms enhance efficiency and profitability of participants and consumer satisfaction. Supply chain activities must be coordinated from market back to producer so that product movement is smooth, efficient and timely.

Technology: new developments must be utilized to optimize handling, storage, transport and quality monitoring and management throughout the supply chain.

Pre-harvest factors affect post-harvest quality, including freedom from physiological and pathological disorders; harvesting at the correct maturity is critical for optimal eating quality. Optimal post-harvest handling can maintain but not improve product quality.

GAPs for harvest and post-harvest management (cont'd)

Handling throughout the supply chain: take care to avoid physical damage and subsequent physiological or physical deterioration. Avoid injuries (cuts, slices, scarring and bruises): keep handling to a minimum and do it gently; transport carefully to the packhouse.

Optimal product temperature minimizes deterioration through respiration, ethylene production and rot development. Remove field heat as soon as possible after harvest: 1-hour delay from harvest = 1 day of shelf-life lost.

Storage at optimum temperature, RH and atmosphere helps ensure optimal quality, consumer appeal and economic returns; avoid chilling injury in chill-susceptible products.

Cleanliness and sanitation are critical: the packing line should be as simple as possible and clean; water for cleaning should be of potable standard or include approved sanitizers; strict worker hygiene must be maintained.

Sorting and grading for uniformity and to prevent damage (e.g. compression, scrapes) that may lead to decay and reduced quality are essential steps.

Packaging for maximum product protection, longevity and promotion is important to maximize post-harvest storage potential and provide consumers with quality products in appropriate, convenient and attractive containers; packaging must meet national or international market specifications, generally being recyclable or returnable.

Internationally accepted pallets must be used, containers aligned perfectly and pallets strapped.

Product knowledge is essential, including market expectations (product specifications, e.g. size, number and maturity) and handling requirements (e.g. temperature, RH and atmosphere, if applicable).

Quality assurance systems, traceability protocols and environmental monitoring systems are necessary during storage and transport to markets.

Staff education and training is essential so that workers understand what they are doing and why; they must be properly equipped, appropriately compensated and praised for a job well done.

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19. Integrated preventive environmental strategy in greenhouse production

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INTRODUCTION TO GREENHOUSE CLEANER PRODUCTION

The United Nations Environment Programme (UNEP) encourages the adoption of sustainable production and consumption practices through the implementation of cleaner production. This is defined as “the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment” (UNEP, 1999). Cleaner production can be applied to the processes used in any industry, to products themselves and to various services provided in society.

The principles of cleaner production also need to be applied to greenhouse production. The five main components of cleaner production are related to conserving raw materials, water and energy, eliminating toxic and dangerous raw materials, and reducing the quantity and toxicity of all emissions and wastes at source during the production process.

Waste reduction

The term “waste” refers to all types, including hazardous and solid waste, liquid and gaseous wastes, waste heat etc. The goal of cleaner production is to eliminate or reduce waste generation. Wastes from a greenhouse vary with different crops, growing technologies and greenhouse structures. Table 1 shows the estimated output of waste from a 1-ha plastic greenhouse with tomatoes grown in non-recirculating perlite as an example.

Non-polluting production

The concept of cleaner production is a closed loop with zero contaminant release; therefore the ideal production process would be the closed greenhouse tending to

TABLE 1

Waste generation for a Mediterranean protected tomato crop

Concept	Material	kg/yr/ha
Roof covering	Low density polyethylene	675–700
Wall covering	Low density polyethylene	50–450
Insect net	High density polyethylene	50–300
Soil mulching	Low density polyethylene	300–650
Bench covering	Low density polyethylene	150–250
Substrate bags	Low density polyethylene	75–100
Irrigation system	Polyethylene	90–150
Training	Polyethylene	70–90
Artificial raffia	Polypropylene	100–225
Boxes	High density polyethylene	200–800
Green biomass (40% wet)		20 000–40 000

zero emissions. Energy, fertilizer and pesticide use are the main processes involved in the production of certain emissions. Table 2 shows the main emissions and the corresponding environmental problems arising.

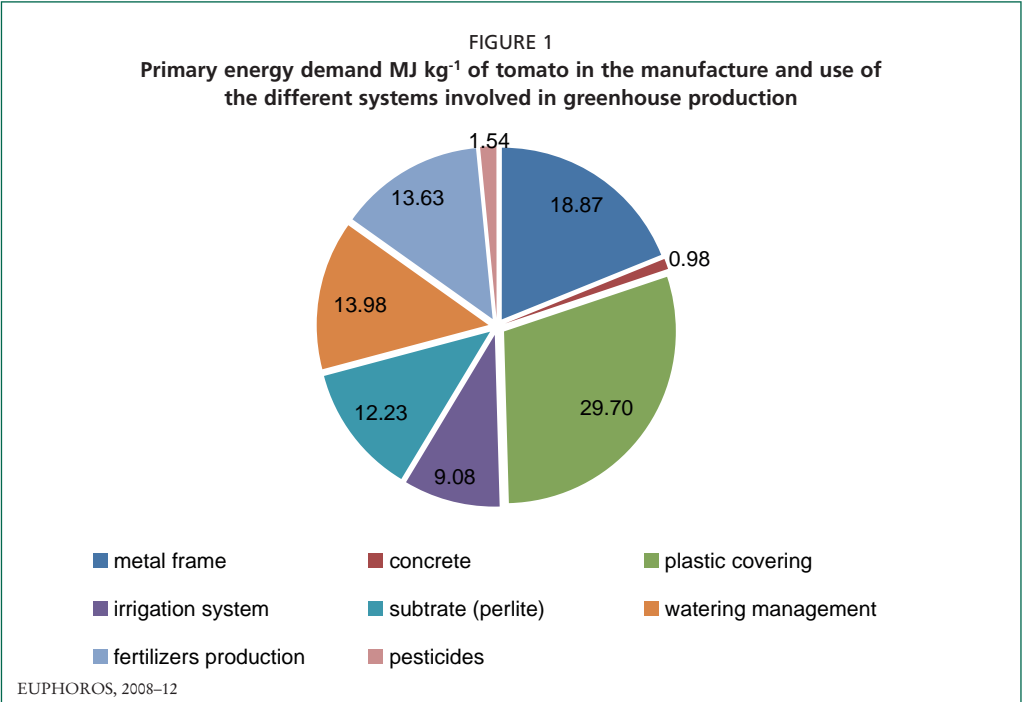
Production energy efficiency

Energy consumption in Mediterranean countries is very different from in northern countries. In a study comparing tomato production, Williams *et al.* (2008) found values of 36 MJ kg⁻¹ in the United Kingdom and 8.7 MJ kg⁻¹ in Spain, including transport from the south of Spain to the United Kingdom. Values of 7 MJ kg⁻¹ have also been reported for the Canary Islands, again including transport to the United Kingdom (Torrellas *et al.*, 2008). For tomato production in a Venlo greenhouse, Torrellas *et al.* (2011) reported a value of 30 MJ kg⁻¹. The extensively cited paper

TABLE 2

Main emissions, environmental impact affected and process involved

Compartment	Release	Environmental impact	Origin
Air	Ammonia NH ₃	Air acidification	Fertilizers
Air	Carbon dioxide fossil CO ₂	Global warming	Energy use
Air	Dinitrogen monoxide N ₂ O	Global warming	Fertilizers
Air	Nitrogen oxides NO _x	Air acidification Eutrophication	Fertilizers
Air	Pesticides	Toxicity	Pesticides
Air	Sulphur dioxide SO ₂	Air acidification	Greenhouse frame Energy use
Soil	Pesticides	Toxicity	Pesticides
Water	Chemical oxygen demand COD	Eutrophication	Greenhouse frame
Water	Nitrates NO ₃	Eutrophication	Fertilizers
Water	Pesticides	Toxicity	Pesticides
Water	Phosphate P ₂ O ₅	Eutrophication	Fertilizers



by Stanhill (1980) gives a value of 7 MJ kg⁻¹ for an unheated glasshouse in Israel with a yield of 20 kg m⁻², and 137 MJ kg⁻¹ for a heated glasshouse in the south of England with a yield of 21.3 kg m⁻², which would now be considered inefficient energy use. In southern Europe, unheated greenhouse tomato production of 1 and 4 MJ kg⁻¹ has been reported by Muñoz *et al.* (2008a) and Torrellas *et al.* (2011), grown in soil and hydroponics, respectively. The differences between the values are quite large, although comparisons were made between the lowest and highest levels of applied technology (Table 3). Although most Mediterranean greenhouses are passive systems with low energy consumption, energy saving could help increase quality and quantity of yields.

TABLE 3
Reported energy demand for greenhouse tomato production in different studies

Country	Energy (MJ kg ⁻¹)	Comments	Reference
Netherlands	30		Anton <i>et al.</i> , 2010a
Colombia	1.1		Medina <i>et al.</i> , 2006
UK	36		Williams <i>et al.</i> , 2008
Spain	8.7	Including transport to UK	Williams <i>et al.</i> , 2008
Spain	1	In soil	Muñoz <i>et al.</i> , 2008a
Spain	7	Including transport to UK	Anton <i>et al.</i> , 2010b
Israel	7		
UK	137		
Spain	3		Torrellas <i>et al.</i> , 2009

Principles of cleaner production

- Waste reduction
- Non-polluting production
- Production energy efficiency
- Safe and healthy work environment
- Environmentally sound products and packaging

Safe and healthy work environment

Cleaner production strives to minimize the risks to workers, making the workplace a cleaner, safer and healthier environment. In the construction and maintenance of greenhouses, a number of situations present risks to the health and safety of workers (mainly falls and accidents due to the use of construction machinery, tractors, mobile elevating platforms and other machinery.) Extreme climate conditions and pesticide use are other risks that must be considered.

Environmentally sound products and packaging

The final product and all marketable by-products should be as environmentally sound as possible. Product packaging should be minimized wherever possible, and where used, it should be as environmentally friendly as possible. Health and environmental factors must be addressed at the earliest point of product and process design and must be considered throughout the product life cycle, from production through use and disposal.

QUALITY MANAGEMENT SYSTEMS

The ISO 9000 family of standards represents an international consensus on good quality management practices. It consists of standards and guidelines relating to quality management systems and related supporting standards. ISO 9001 specifies requirements for a quality management system where an organization wishes to demonstrate its ability to provide products that consistently meet customer needs and the necessary regulatory requirements. It attempts to promote customer satisfaction by applying the system effectively.

Certain processes are included to continuously improve the system, assuring conformity to the customer as well as to the appropriate regulatory needs. It is a certification of internationally accepted standards (ISO-9001, 2008).

Continuous improvement

- Planning
- Doing
- Checking: use of indicators and devices to register
- Acting or implementing

In protected horticulture, the adoption of continuous improvement must also be considered. In order to optimize greenhouse production, it is necessary to adopt the Deming Cycle: Plan-Do-Check-Act (PDCA), also known as Plan-Do-Study-Act (PDSA). Suitable indicators to evaluate the installations and record their values over time must be identified, using devices such as water counters, energy controllers and climatic sensors.

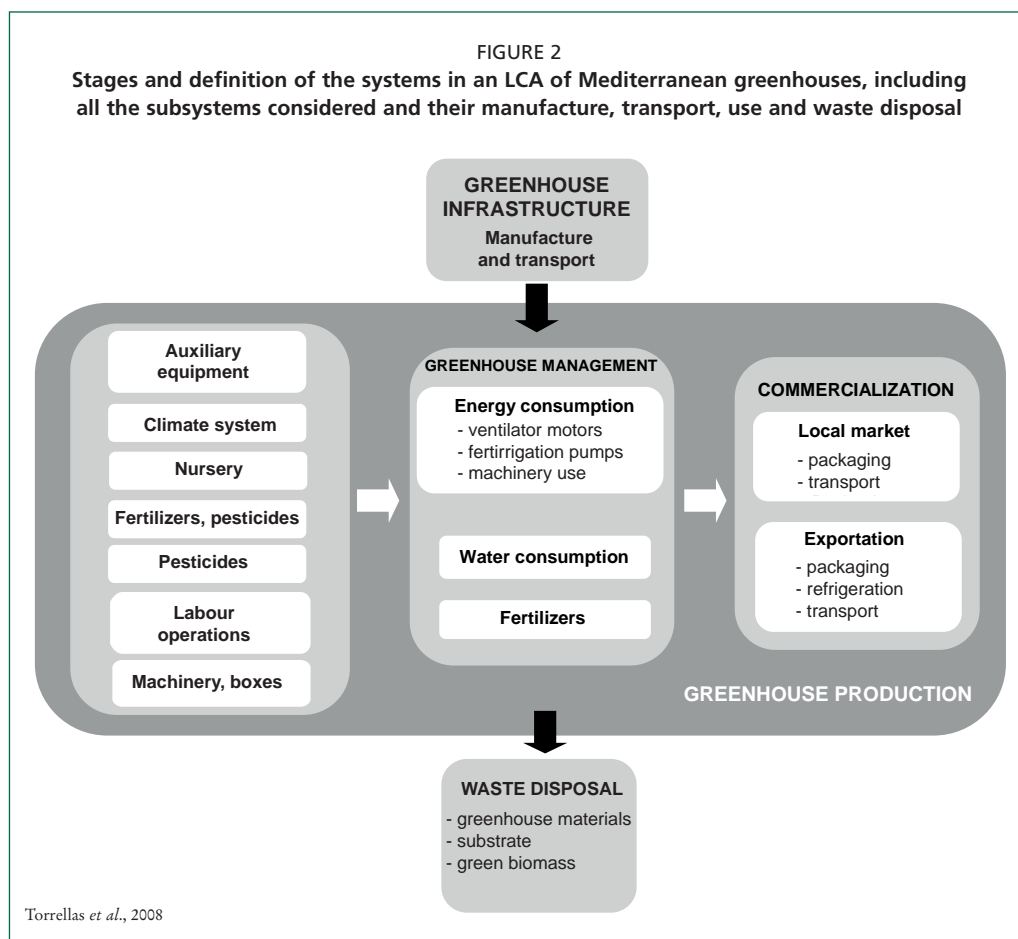
ENVIRONMENTAL MANAGEMENT – LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a tool for assessing the potential environmental impact of a product or system, considering the product's life cycle from resource extraction to waste disposal. ISO standardization provides guidelines to follow in an LCA study to guarantee objectivity. According to the ISO-14040 (2006) guidelines, an LCA study can be divided into four phases:

- definition of goals and scope
- analysis of inventory analysis
- impact assessment
- interpretation

Goal and scope definition

This is the phase in which the initial choices that determine the working plan for the whole LCA are made. The scope of the study is defined in terms of temporal, geographical and technological coverage. The level of detail of an LCA



depends on the subject and the intended use of the study. It is during this phase that each functional unit (FU) is also defined. The FU describes the primary function of a product system; for example, if product supply is the function under consideration, the FU may be yield per square metre. The FU provides a reference to which input and output data can be normalized mathematically. Comparability of LCA is particularly critical when different systems are being assessed. To ensure that comparisons are made on a common basis, the same relevant service must be considered – not always obvious in agricultural products (provision of food or nutrients, production of yield, earning money etc.).

Inventory analysis

The life cycle inventory (LCI) phase is the second phase of an LCA. The inventory analysis lists all extractions of resources and emissions of substances attributable to the FU under consideration. This involves the collection of the data required to meet the goals of the defined study. To be precise, an allocation of the input and output flows has to be performed in processes in which two or more products are produced or sub-produced. Allocation is a complex issue and is particularly relevant in agricultural production because agricultural systems are characterized by closely interlinking subsystems of activities (Audsley, 1997).

Impact assessment

The impact assessment phase of an LCA aims to evaluate the significance of potential environmental impacts using the LCI results. The final goal is to have information about how an activity, process or product can affect different areas of protection (AoP): human, health, ecosystem quality and resource use. A series of different environmental categories are assessed: midpoint when closer to an impact pathway; endpoint when closer to an AoP.

- Midpoint categories comprise classical impact assessment methods – CML (Guinée *et al.*, 2002) or EDIP (Hauschild and Wenzel, 1998) – restricting quantitative modelling to relatively early stages in the cause-effect chain.
- Endpoint categories comprise damage-oriented methods – Eco-indicator 99 (Goedkoop and Spriensma, 2000) or EPS (Steen, 1999) – which try to model the cause-effect chain up to the endpoint or where damage occurs (directly correlated to AoP).

The main contributions to impact in Mediterranean greenhouses are structure and fertilizer use.

Interpretation

Interpretation is the final phase of an LCA; conclusions are drawn, recommendations made. The results of the analysis and all the choices and assumptions made are discussed, and opportunities to reduce the environmental impacts of the FU, such as changes in product, process and activity design, raw material use, industrial processing and waste management, are identified and evaluated. From studies in

Mediterranean greenhouses (Antón *et al.*, 2004), the following conclusions can be made:

- The greenhouse structure has the greatest impact in most environmental categories except the toxicity indicators. This is due to the relatively short life span of plastic-covered greenhouse structures with minimal inputs of external energy in the production process.
- Further research must look to reducing the environmental impact of the materials used in the structures for passive greenhouse crops. Substitution with recycled materials with a longer life span is a possible solution.
- The types of cladding compared in this study (PC sheet and LDPE film) are not particularly important in environmental analysis.
- Improving fertilizer use and looking for alternative local substrates, preferably derived from reused materials, are other important factors to take into account.

Environmental bottlenecks

- Use of fertilizers
- Use of substrates
- Water use
- Waste management
- Infrastructure and equipment
- Logistics
- Energy use

OCCUPATIONAL HEALTH AND SAFETY MANAGEMENT SYSTEMS

OHSAS 18001 is a certifiable standard based on continuous improvement, written by an international consortium led by the British Standards Institution (BSI). It describes the minimum requirements for an occupational health and safety management system to enable an organization to formulate policy objectives, taking into account legislative requirements and information on significant hazards and risks which the organization can control and over which it can be expected to have an influence, in order to protect its employees and others whose health and safety may be affected by the activities of the organization.

This section provides a brief description of the risks associated with greenhouse production and of the preventive measures to adopt. Any protocol to prevent health and safety risks in the greenhouse should comply with the law of the country and be accompanied by the company's commitment to maintain a policy of prevention and continuous improvement. Risk prevention in greenhouses should focus on the greenhouse construction, maintenance and work culture.

Greenhouse construction and maintenance

Various situations arising in the construction and maintenance of greenhouses may constitute a health and safety risk for workers. As most risks are not specific to greenhouses but are derived from construction activities (laying foundations, building the structure, installing vent openings etc.) or maintenance (changing plastics, liming etc.), the preventive measures taken in a greenhouse should be the same as those taken in any construction activity or maintenance work. However,

certain risk-associated tasks typical of greenhouse building and maintenance should be highlighted:

- installation of plastic, glass and ventilation structures
- renovation, bleaching or cleaning of plastic

These tasks require work at the height of the infrastructure and pose a major risk of falls and accidents; they should therefore be viewed as for working on a high building. As a general rule, workers should use scaffolding, lifting platforms and safety harnesses.

Greenhouse management

Tasks inside the greenhouse involve a number of potential risks in addition to the usual risks of working in agriculture.

Safety risks

- Fall from heights during harvest.
- Entrapment by overturning or collapsing mobile elevating platforms.
- Tractors overturning.
- Falling objects, such as shading nets and strengthening arches.
- Use of construction machinery adapted for use in a greenhouse without the necessary safeguards.
- Electrical contacts with power lines during cleaning or replacement of plastics.

Hygiene risks

- Heat stroke due to unfavourable hygrometric thermal exposure conditions – evaluation using standardized methodologies (WBCT Index) required, as well as rehydration areas, breaks etc.
- Application and use of plant protection product – risks as for outside, but aggravated by high temperature, humidity and use in enclosed area. Legal measures should be established in each country; “No trespassing” signs need to be installed during treatment.
- Exposure to pesticide residues for workers entering treated fields or greenhouse facilities. The worker exposure scenario and individual work practices determine worker risk exposure (e.g. during tomato reach-and-pick work, dermal exposure is estimated at 0.10 mg of pesticide per kg of body weight per day; exposure risk for an applicator is 0.0012 mg active ingredient per kg of body weight per day – Whitford *et al.*, 1999).

Ergonomic risks

- Back injury as a result of awkward posture and manual handling of loads.

Occupational health and safety – Summary

Greenhouse construction and maintenance:

- Risk of falling during installation of plastic, glass and ventilation structures
- Risks associated with the renovation, bleaching or cleaning of plastic

Greenhouse management:

- Safety risks: falls, use of platforms, tractors, construction machinery and electric contacts
- Hygiene risks: hygro-metric thermal exposure and pesticide exposition (during application and other works)
- Ergonomic risks: awkward postures and handling loads

POLLUTION PREVENTION

Air emissions: CO₂ equivalents, N emissions, pesticides

CO₂ release is mainly related to energy use. While most Mediterranean greenhouses in the horticultural sector are passive (i.e. without heating or lighting), alternative energy sources (not fossil fuels) must still be sought since, for example, large quantities of fossil fuels are used to manufacture nitrogen fertilizers. Many energy companies offer “green power”, produced from renewable energy sources such as wind, hydro and solar. It costs a little more than conventional power, but the extra cost can be covered by improving energy-use efficiency.

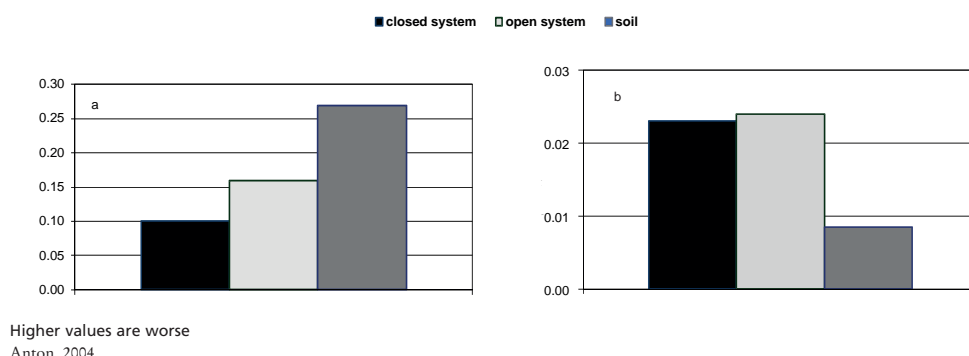
Nitrous oxide from agriculture is released from nitrogen compounds present in manure, fertilizers, crops, soils and watercourses. It tends to be produced in oxygen-free conditions. The most effective way to reduce the release of this gas is to use nitrogen fertilizers and manures efficiently so that the crop requirement is met while losses of nitrogen are minimized.

Water pollution: NO₃, P and pesticides

Groundwater can become contaminated by greenhouse fertilizers, pesticides, washdown waters, and roof shading and cleaning; if a substrate is used, this too has potential environmental consequences.

Figure 3 compares closed systems with free drainage and soil cultivation. While eutrophication clearly improved in closed systems, other factors (e.g. the depletion of non-renewable resources and the formation of photochemical oxidants) increased due to the greater quantity of materials used in these systems. Once collected, the solution is immediately recirculated or held for later recirculation. In both cases, the solution may have to be reconditioned for reuse. Collecting, treating and recycling greenhouse effluent is one of the best solutions to this environmental problem.

FIGURE 3
Comparison of environmental impacts for closed systems, with free drainage and soil cultivation:
a) eutrophication, kg P₂O₅ per kg tomato and
b) depletion of non-renewable resources, per year per kg tomato



At some time, in particular in Mediterranean conditions, some or all of the nutrient solution must be disposed of, owing to salt imbalance, disease or contamination, or because the end of a crop cycle has been reached. Disposal is potentially polluting, therefore the method of release must be chosen with care. The preferred methods are: release to sewage systems or holding/settling ponds; or as irrigation water to adjacent field crops. The least preferred is discharge into tile drains or surface water.

For most crops there is potential for fertilizer reduction. For example, with tomato, Muñoz *et al.* (2008b) showed that fertilizers can be decreased from 11 to 7 mmol/litre of N without affecting yields and reducing the environmental impact by nearly 50 percent.

Recycling of materials

Greenhouses produce large amounts of waste; in particular, greenhouse production systems create large quantities of solid waste (steel, plastics and non-yield biomass).

There is increasing use of recirculated or closed systems in order to reduce pollution associated with the use of fertilizers and to save water. These are cultivation systems in which the water drained from the root zone is collected and reused to irrigate the same crop. However, soilless closed systems require additional material (benches, collection pipes, bags of substrate, soil covering film etc.), generating a large quantity of waste.

At the end of their “life”, these materials are traditionally incinerated or disposed of in a landfill. Some companies recycle plastics, but recycling costs vary: they depend not only on the material, but also on market-determined factors,

such as the price of the materials made from primary sources and the quality and quantity of the material available for recycling. Recycling plastic is generally more expensive than the market price of the recycled product and must therefore be subsidized.

Wherever possible:

- **reduce**
- **reuse**
- **recycle**

In addition, there is an annual non-yield biomass of 7 000–20 000 kg/ha of dry matter, depending on the crop. Various options are available for the treatment of this non-yield biomass: landfill disposal or incineration if there is no segregation from other materials; or composting by facilities based on low technology processes (turned windrow composting or composting in confined windrows). For areas of high production or for more developed productions, the organic fraction can be treated in plants based on more technological complex processes (composting in-vessel or anaerobic digestion plus composting).

Plastics

Plastics – plastic film from greenhouses, ground covers and substrate bags – are major sources of waste. The technology exists to recycle plastic film, but recycling companies want the plastic to be dry and clean, and this can be difficult.

If plastic items such as plant trays are reused, choosing more durable products can increase their life. The manufacturer should be contacted to see if a recycling system is in place. Finally, a promising option for the future is the use of biodegradable materials, especially when they are in contact with the plant, such as trellising clips or soil mulching.

Steel

Although most of the frame of commercial greenhouses is made of recycled steel, the alternative use of local materials should still be considered. Simple structures (wood and plastic), with their low-level technology and associated low energy consumption, have a lower environmental impact than medium level (steel and plastic) and more complex (aluminium and glass) structures (Russo and Scarascia-Mugnozza, 2004). Medina *et al.* (2006), using LCA methodology, provide an overall picture of energy costs and environmental burdens associated with greenhouse tomato production in the Bogota Plateau (Colombia), showing the very low energy use associated with the low level of technology used there.

Substrate

Peat from peat bag culture (tomatoes, cucumbers) can be recycled and used by landscape firms. Peat is organic, environmentally friendly and people are eager to use it for landscaping and gardening. However it is a natural resource and its use has an environmental impact associated with the depletion of renewable resources.

Priorities in pollution prevention

- Reduce: energy saving, fertilizer dosification, pesticide use
- Recirculate: closed systems
- Reuse: materials, lixiviates in adjacent field crops etc.
- Compost: green biomass
- Recycle: plastic materials, substrates, composting
- Other disposal methods or treatments

Inorganic substrates (e.g. rockwool) do not decompose and must be dumped in landfill sites. Recycling of rockwool must be offered by suppliers, who should in turn have recycling procedures. Inorganic expanded clay (e.g. perlite) does not break down and, with sterilization, could be reused; it is still undergoing development. Other substrates include coconut fibre and stonewool.

Composting of green biomass

Studies show that source segregation followed by the composting of biodegradable

matter is the best way of managing waste and reducing the impact in most of the categories considered. The maximum reduction in the environmental impact by segregation of non-yield biomass and its subsequent composting is that relating to climate change. The impact in this category could be reduced by 40–70 percent, depending on whether landfill or incineration is considered (Antón *et al.*, 2005).

Disposal: landfill, incineration, others

Historically, collected waste went to the local dump where open burning was used to reduce its volume. More recently, waste management technologies have become increasingly sophisticated, but the success rate depends also on the retailers (not all are involved) and on existing government regulations, which are not the same throughout the Mediterranean.

CONCLUSIONS

Sustainable management in greenhouse production means production of high quality food with guaranteed use of environmentally friendly renewable energy and raw materials. In rural areas, it also entails positive economic development by generating jobs and income. Greenhouse production in the future must be sustainable and productive, while conserving natural resources for coming generations. In summary, for an integrated preventive environmental strategy in greenhouse production, the following recommendations are made:

- Be aware of the life cycle approach to avoid externalizing impacts.
- Optimize doses of fertilizers and pesticides.
- Implement an efficient system of waste management: reduction, recycling, treatment and disposal.
- Develop occupational health and safety policies.

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20. Product safety

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INTRODUCTION

In fruit and vegetable supply chains, food safety is an increasingly important factor. This chapter provides a reference guide for the inclusion of food safety in training programmes for farmers and workers in greenhouse vegetable production in the Mediterranean region. Greenhouse cultivation has extended significantly in the Mediterranean region during the last 30 years, and there is still wide scope for improvement. With greenhouse cultivation systems (glass or plastic film cover, low or walking tunnels etc.), it is possible to regulate the environmental conditions, extend the crop growing and harvesting period, safeguard product quality and improve market access. Food safety issues are relevant to all these areas.



HTTP://WWW.IPM-NEAREAST.COM/

Plate 1

Greenhouses in Mediterranean context

Health (consumer protection) is the main entry point for food safety herein. However, under certain conditions, marketing benefits may also result from improved food safety and quality. Food safety of fresh produce is all the more important in view of the dramatic increase in human health problems related to unhealthy dietary patterns (e.g. diabetes type 2, coronary heart diseases, some cancers). Increased consumption of fruits and vegetables is high on policy agendas, and food safety, therefore, plays a major role in consumer acceptance and thus marketing opportunities.

This chapter has been adapted from the Food Safety Manual for farmer field schools (FFS), developed in 2010 for the FAO Plant Production and Protection

¹ The authors worked on a previous document, *Food safety manual for farmer field schools*, by Frederike Praasterink, Harry Van der Wulp, Anne Sophie Poisot, Marjon Fredrix, Catherine Bessy, Alfredo Impiglia, Alma Linda Morales Abubakar, Areepan Upanisakorn and Jan Ketelaar.

Division (AGP) and the Food Safety and Quality Division (AGN) in collaboration with staff of three FAO regional IPM programmes. The FFS manual should be referred to for more complete information and detailed exercises for field implementation. Much of the content of the manual is based on field experiences of FFS programmes in Asia, West Africa, and the Near East and North Africa (in the latter case involving greenhouse vegetable production). Background information is from various sources, including ASEAN (Association of Southeast Asian Nations) GAP training materials.

This chapter focuses on the safety of vegetables during pre-production, production, harvest and post-harvest on-farm: the first part describes general aspects of food safety and food quality, and lists a number of food safety hazards; the second lists good farming practices (good agricultural practices) to increase food safety in fruits and vegetables.

WHAT IS FOOD SAFETY?

Food is considered safe when there are no negative effects on consumer health due to contamination: food safety is the absence of adverse health effects resulting from food contamination. It is a scientific discipline that identifies the production, handling, preparation and storage procedures of food so as to prevent food-borne illness.

Food safety is very important for:

- consumer health protection – people should not get sick from eating contaminated food.
- market access – some national governments or retailers require food safety certificates; if farmers do not produce according to specific criteria (e.g. maximum residue levels for pesticides), they cannot sell produce through those markets and when there is significant occurrence of food-borne illness in a region, international markets can be stricter about acceptance of food products from that region.

Food safety hazards are any chemical, biological or physical substance or property that can cause fruits and vegetables to become an unacceptable health risk to consumers. Chemical hazards may include heavy metals, or pesticide residues exceeding maximum authorized levels; biological hazards include pathogenic bacteria (e.g. *E. coli* or *Salmonella*), parasites and viruses associated with the crop; physical hazards can be pieces of glass or stones in the product.

Attention to food safety is increasing for a variety of reasons:

- Increase in global trade
- Production in new areas with less developed food safety programmes
- New (convenience) products, such as fresh-cut fruit and vegetables and salads

- New production, processing and storage methods
- Scaled-up production to meet increasing demand without adequate risk analysis
- Emerging micro-organisms with different levels of virulence and persistence
- Introduction of new organisms into regions
- Changes in people's susceptibility and awareness

Eating contaminated food can have acute or long-term effects. An acute (immediate) effect is people getting sick (e.g. vomiting, diarrhoea) shortly after eating contaminated food. Long-term (chronic) effects are related to long-term consequences of acute infections (e.g. Shiga toxin producing *E. coli*), or may result from a gradual buildup of unhealthy substances (chemicals or toxins) in the body – at very high levels, people get sick and may even die (e.g. toxic levels of cadmium in human kidneys).

WHAT IS FOOD QUALITY?

Food quality is the combination of a product's characteristics valued by the consumer. Food quality is subjective: it means different things to different people and may take into account any of the following:

- nutritional factors (e.g. vitamin content)
- sensorial properties (e.g. taste, smell)
- appearance (e.g. colour, size, firmness, absence of bruises and damage)
- social considerations (e.g. traditions, food culture)
- convenience (e.g. preparation, shelf-life, easy peeling)
- food safety

There is a growing demand for improved quality of food due to globalization of trade and markets (creating a need for standardization of production and quality of food), changing lifestyles (more convenience food, and increased consumption of meat and dairy) and a growing number of food safety outbreaks. Most consumers buy food based on appearance, price and convenience. Food safety is often not specifically considered, because it is assumed by consumers that fruit and vegetables are healthy and safe to eat. Unfortunately, this is not always the case. Many farmer interventions to improve the safety of fruits and vegetables also help improve the quality.

FIGURE 1
The relationship between food safety and quality



Factors affecting both food safety and quality

- **Seeds.** Good quality and from a safe source, affect performance, provide variety demanded by the market.
- **Soils (or substrate, such as hydroponics).** Location chosen in consideration of safety and quality of soils, soil preparation method.
- **Plant management.** Spacing, weeding, minimizing mechanical injury pre- and post-harvest.
- **Water.** Quantity, quality, irrigation techniques.
- **Fertilizers and soil amendments.** Major influence on shape, shelf-life, taste (e.g. sugar content of fruit) and contamination; organic fertilizers do not imply exclusive rights to good taste or increased safety.
- **Diseases and pests.** IPM, timing and quality of pesticide used (consumer choice of good-looking versus chemical-free produce), general greenhouse hygiene and maintenance influencing pest population levels.
- **Post-harvest handling.** Maturity stage, harvesting techniques, equipment and hygiene, time of harvest, sorting and grading practices and hygiene, washing prior to sale in clean water and appropriate use of sanitizers, hygiene and maintenance of equipment and facility, human contact etc.
- **Storage.** Conditions, length, use of preservation chemicals, storage containers and storage atmospheres.
- **Transport.** Packaging quality, storage time and temperature, means of transport etc.

WHO IS RESPONSIBLE FOR FOOD SAFETY?

The food chain is the process from farming to consumer: along this chain food is produced, manipulated, transformed, packaged, stored, transported and consumed by a range of stakeholders, each of which influences product safety. The efforts of some stakeholders to produce and maintain a safe product can easily be ruined by others not paying attention to hygienic prescriptions related to the activities under their responsibility. All players in the food chain are responsible and must share a common goal: ensure safe food at all steps in the chain.

Among these stakeholders, farmers have responsibility for food safety before and during production, harvest, post-harvest and on-farm storage. Food contamination can also occur further down the food chain and that is – in most cases – beyond the responsibility and control of the farmer. However, the level of pre-harvest contamination determines the effectiveness of control measures through the rest of the food chain. Once a product becomes contaminated it is very difficult to remove the contamination.

Governments have overall responsibility for national food safety policies and their enforcement.

This manual focuses on agricultural production, and it is therefore important to carry out a detailed analysis of what farmers can do to prevent food safety hazards. It is necessary to be critical but also realistic with regard to potential improvements using appropriate farming practices. When more prominent risks arise later in the food chain, partnerships could have a role in guaranteeing food safety, for example, with farmers working together in associations or making longer-term marketing arrangements with middlemen or with contract growers for a processing factory.



Plate 2
Farmers marketing IPM vegetables

BETTER OPPORTUNITIES WITH IMPROVED FOOD SAFETY

Safe food is expected by consumers and the food chain has a responsibility to produce it. Market access is an important driver within the food chain and can be central in specific areas, but it should not be the only driver or the sole reason for attention to and development of a strategy for food safety.

Implementing activities at farmer level to improve food safety and quality may be cumbersome, in terms of both money and time (e.g. record-keeping). Farmers may be motivated by good product prices (cost-benefit) or by the potential to maintain market access. Training is often necessary to understand the importance and benefits of food safety and product quality. For example, farmers using integrated pest management (IPM) often use fewer pesticides than conventional farmers, benefiting both the environment and workers (Sette and Garba, 2009; Near East IPM programme). Some farmers try to market their IPM produce as “safe” or “clean”. However, in many countries safer food products cannot be recognized by consumers or buyers since there is no official certificate or logo. In addition, most consumers buy products on the basis of quality attributes (e.g. appearance, taste and shelf-life), simply assuming the food is safe. If safe produce is to reach better markets, it

Safer produce profitable for farmers: the Palestinian case

Impact studies by An Najah National University (2006–09) revealed the following results on the impact of the IPM/FFS approach:

- Greenhouse cucumber: reduction in use of insecticides (40%), less in fungicides (35%), no significant change in herbicides.
- Greenhouse tomato: reduction in use of insecticides (55%), fungicides (40%), no significant change in herbicides.
- Reduction in total input costs of about 20%, while yields increased on average by 15% providing a notable improvement to the farmers revenue.

TABLE 1

Reduction of hazard in controlling leafminer (*Liriomyza trifolii*)^a

IPM measure	Notes
Parasite wasp <i>Diglyphus isaea</i>	Tested, effective
Hunter fly (<i>Coenosia attenuata</i>)	Tested, effective
Yellow sticky traps	Used as a monitoring tool, not as a control method
Fine wire mesh screens	Used to keep the insect out of the greenhouse
Asafetida plant solution	Applied as a repellent
Neem extract	Sprayed
Plastic mulch	Placed to collect aphids falling off the plants
Weeding done, in particular of Solanaceae	Collected weeds buried for composting
Affected leaves removed	

^a Leafminer was the target of up to 15 insecticide applications per season on tomato. IPM measures were applied, obtaining 50 percent reduction in use of insecticides.

should also display other quality attributes; it would therefore be useful if training programmes for IPM farmers also integrated quality aspects.

Some countries have come up with activities to promote IPM produce, creating logos or labels (e.g. in Jordan) or establishing direct sales to supermarkets or hotels. There is no single answer to whether better food safety at production level leads to improved marketing opportunities and higher prices. It depends on the local conditions and market requirements – both local and for export. Trainers must help farmers understand requirements for specific market opportunities; within FFS training in West Africa, for example, food safety aspects are taken into account in market research. Examples of linking farmers to markets can be found on the FAO internet site (e.g. the one-page case study found at www.fao.org/ag/ags/subjects/en/agmarket/linkages/index.html).

IS FOOD SAFETY NECESSARY FOR ALL FARMERS?

From a public health perspective, food safety is necessary. It is also important from an economic and market access point of view. Safe food is also essential for the domestic market, as importers look at local food safety aspects when selecting trading partners.

All farmers must apply good farming practices to produce safe food. However, not all countries have appropriate guidelines, certification and training programmes and controls on food safety issues. Often, it is more difficult for small farmholders to comply with good agricultural practices than it is for large farmholders. Trainers should raise awareness of basic food safety principles and concepts; they need to understand the main food safety risks in a community and then work with farmers to identify them and introduce feasible practices to improve food safety. It is important that food safety is integrated into training programmes.

TABLE 2
Chemical hazards

Hazards	Causes of contamination (examples)
Pesticide residues in produce exceeding maximum residue limits (MRLs) ^a	Pesticide not approved for target crop Incorrect mixing and higher than recommended dosages Withholding period (harvest interval) not observed Equipment faulty or not calibrated Pesticide residues in soil from previous use Dumping or accidental spillage of pesticide into soil or water source
Non-pesticide contamination such as lubricants, cleaners and sanitizers, paint, refrigerants, vermin control chemicals, fertilizers, adhesives, plastics	Inappropriate chemicals used for cleaning and sanitation Oil leaks, grease, paint on equipment in contact with produce Residues in picking containers used to store chemicals, fertilizers, oil, fuel Spillage of chemicals (lubricants, cleaners, vermin control chemicals) near produce and packing materials
Heavy metal residues (cadmium, lead, mercury) in produce exceeding maximum levels	Continued use of fertilizers (including compost) with high levels of heavy metals Use of improper domestic compost containing batteries (cadmium, mercury) Lead contamination from car exhaust fumes if farm is near busy road High levels of heavy metals in soil naturally or from previous use or leakage from industrial sites Use of contaminated water for irrigation or municipal sludge
Natural toxins – allergens, mycotoxins, alkaloids, enzyme inhibitors	Unsuitable storage conditions – for example, storage of potatoes in light
Allergenic agents	Traces of a substance that causes a severe reaction in susceptible consumers – for example sulphur dioxide used to prevent rots on grapes

^a The Codex MRL (maximum residue level) database <http://www.codexalimentarius.net/pestres/data/index.html> is an internationally recognized source for information about MRLs. The generic trend is that national MRLs are aligned with the Codex MRLs, although discrepancies exist. However, specific markets may have their own requirements that complement Codex and they must be checked for a specific location or conditions.

TYPES OF FOOD SAFETY HAZARDS

There are various types of food safety hazards, including chemical, biological and physical; examples are described below.

Chemical hazards

Harmful chemicals at high levels have been associated with chronic illness and death, for example, after eating food with high pesticide residues. In many developing countries, pesticides from vegetables are a major food safety risk, especially if long-term exposure – leading to chronic conditions and consequent pathologies – is taken into account.

Biological hazards

Micro-organisms or microbes are small organisms visible only through a microscope. They are found everywhere in the environment: fruit and vegetables contain a dynamic and diverse mixture of micro-organisms, and products handled daily may contain as many as 100 million organisms per gram – normal inhabitants that do not affect the health of consumers. There are three types of interaction with food:

- Beneficial – acts on food to produce desirable quality characteristics, such as aroma, texture, microbiological stability (e.g. yeast and fungi for making cheese such as Danish Blue).

- Spoilage – produces undesirable quality characteristics such as softening, bad odour and flavour (e.g. fruit rots).
- Pathogenic – affects consumer health, with illness caused either by the micro-organism itself growing inside the human after eating (infection) or by toxins produced by the micro-organism (intoxication).

In the case of pathogenic interaction, the most common types of micro-organism are bacteria, parasites and viruses.

Bacteria

The most common cause of food-borne illness, bacteria require nutrients and appropriate environmental conditions to grow. They can grow rapidly under appropriate conditions in a very short time – in 7 hours, one bacterial cell can generate over a million cells. Common pathogenic bacteria linked to contamination of fresh fruit and vegetables are:

- *Salmonella* species
- *Escherichia coli* (*E. coli*) pathogenic strains
- *Campylobacter* species
- *Listeria monocytogenes*
- *Bacillus cereus*

Some bacteria can be found in the soil (*Listeria* sp., *Bacillus cereus*) and contamination may occur directly via contact with the soil or with dirty containers and equipment. Other bacteria pass through the intestinal tract of animals and humans, and fruits and vegetables become contaminated either through manure or contaminated soil and water, or when humans handle produce.

Parasites

Parasites inhabit another living organism – the host. While unable to multiply outside an animal or human host, they can cause illness with only a low number of organisms. Fruit and vegetables are potential vehicles for passing parasites from one host to another: animal to human or human to human. Cysts, the dormant phase of parasites, that aid survival in unfavourable environmental conditions, remain infectious for many years in the soil (e.g. *Giardia*). Water contaminated with faecal material, infected food handlers and animals in the field or packing shed are all potential vehicles for contamination of produce with parasites. Parasites commonly associated with contaminated fruit and vegetables are:

- *Cryptosporidium*
- *Cyclospora*
- *Giardia*
- Helminths

Viruses

Viruses are very small and unable to reproduce outside of a living cell. Human enteric viruses do not grow in or on fruit and vegetables; however, produce can act as a vehicle to pass viruses from animals to humans or from humans to humans. Low numbers of surviving viruses on produce can cause illness. Viruses passed to humans through contaminated produce are:

- Hepatitis A
- Norovirus

Physical hazards

Physical hazards are foreign objects that can cause illness or injury to consumers. Contamination can occur during production and post-harvest handling. Physical hazards include glass, wood, metal, plastic, soil and stones, personal items (e.g. jewellery, hair clips), paint flakes, insulation, sticks, weed seeds, toxic weeds.

Other hazards

Food safety hazards may also occur through genetically modified organisms (GMOs), which may cause allergic reactions. Nano-technology (e.g. nano-pesticides) can also cause food safety hazards (Nanoall, 2010). Further research is required in order to better understand the associated hazards.

Factors affecting risk of biological contamination

How the produce is grown:

- Products grown in the ground (carrots) or close to the ground (lettuce or melons) are at higher risk than those grown well above the ground (tomato and pepper).
- Products in frequent contact with water are more exposed, and risk therefore increases (e.g. hydroponic production).

Product surface:

- Products with a large uneven surface (melon with netted rinds, lettuce and strawberries) are at greater risk than those with a smooth surface (eggplant).

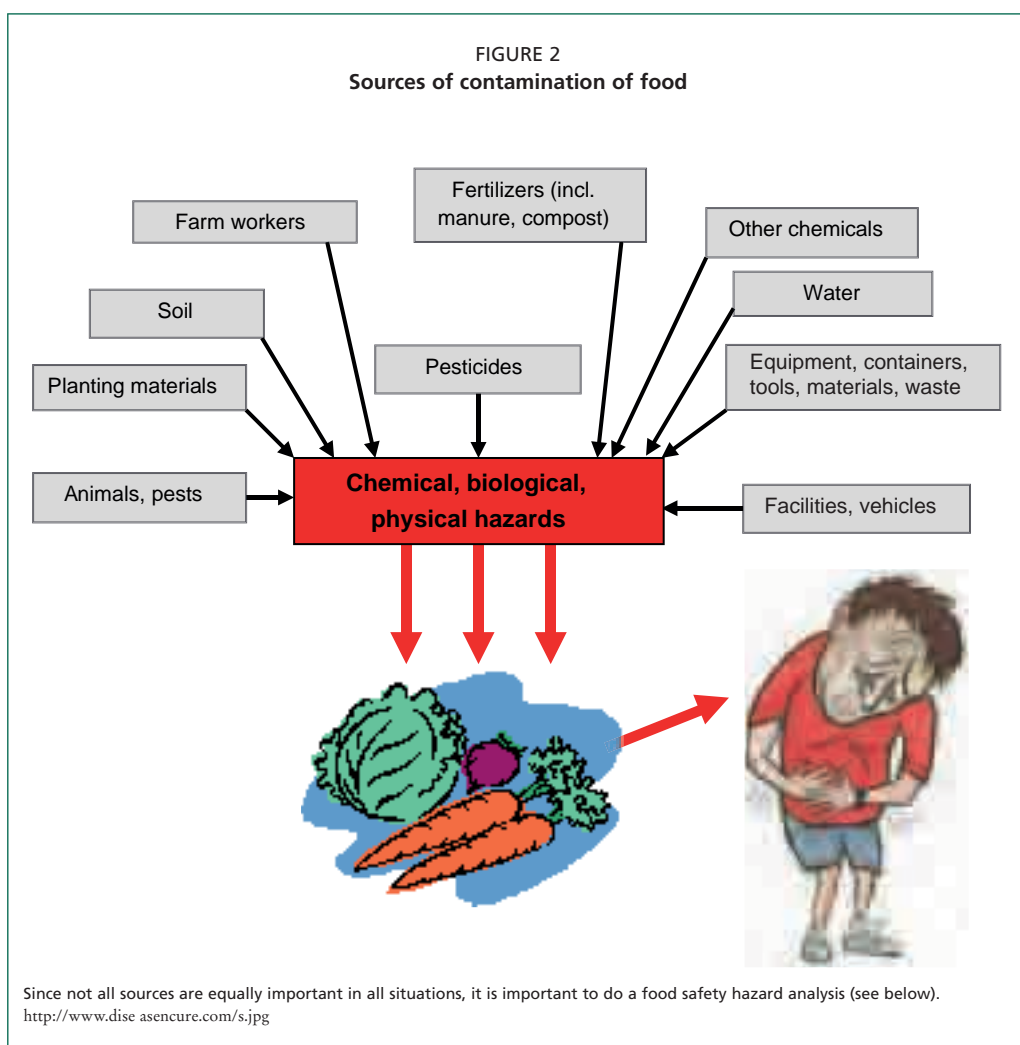
How the produce is consumed:

- Products eaten raw (leafy vegetables) are at higher risk than cooked produce (potato).
- Products with edible skin (strawberry) carry a greater risk than products with inedible skin.

TABLE 3
Physical hazards

Hazards	Causes of contamination (examples)
Foreign objects from the environment – soil, stones, sticks, weed seeds	Harvesting of ground crops during wet weather Dirty harvesting and packing equipment, picking containers, packaging materials Stacking of dirty containers on top of produce
Foreign objects from equipment, containers, buildings and structures – glass, wood, metal, plastic, paint flakes	Broken lights above packing equipment and areas where produce is exposed Damaged picking containers, harvesting and packing equipment, pallets Inadequate cleaning after repairs and maintenance
Foreign objects from human handling of produce – jewelry, hair clips, personal items	Careless or untrained staff Inappropriate clothing

FIGURE 2
Sources of contamination of food



Food safety hazard analysis

Obviously, not all sources of contamination are applicable to all farms; it is important to carry out a detailed hazard analysis to identify the main sources of food safety problems. It is then easier to define the steps to avoid contamination.

Facilitators, trainers or national extension programme coordinators may need the assistance of a local food safety expert for a comprehensive hazard analysis of the crops and locations selected under the programme. When possible, facilitators and trainers should be involved in the analysis in order to improve their skills. A participatory hazard analysis is a good exercise for the farmers' group: it can be a basis for identifying good practices to minimize risk, which can then be addressed during training and tested on the farms.

GOOD AGRICULTURAL PRACTICES TO MANAGE FOOD SAFETY

Activities conducted to produce safe food are called good farming practices or good agricultural practices (GAP). Good farming practices reduce or prevent food safety hazards. GAPs for vegetables grown in greenhouses to avoid food safety hazards linked to different sources of contamination (Figure 2) are detailed below. They must be applied at all stages of crop production: from planning and preparation of the soil and growing area, to planting, crop and greenhouse management, harvesting and post-harvest handling. All people working on or entering the farm are involved and should be aware of their responsibilities in the production of safe food. Training of farmers, farm workers and associated groups, such as packers and transporters, may be necessary.

An example of hazards and good farming practices for various cropping stages or greenhouse and farm operations is given in the Food Safety Manual for FFS (farmer field schools). Since most training programmes follow the cropping cycle, it makes sense to add food safety elements according to cropping stages. A number of structured learning exercises can be done with greenhouse farmers and workers to list and practise good farming practices applicable to a specific crop and location. It is important to be very practical and work with those practices that are relevant to the greenhouses. Facilitators can help the FFS group identify and prioritize food safety hazards and select good farming practices that are appropriate and locally feasible for their control.

CONCLUSION

This chapter provides a context for food safety, indicates potential sources of hazards and specifies measures to address concerns related to food safety issues. These measures should be adapted to local conditions and considered alongside the GAPs provided in other chapters of this book. Addressing food safety issues in vegetable production can provide improved nutrition at local level, as well as increased access to market opportunities.

Site history and management

Food safety hazard: Chemical and biological contamination of produce from prior use of the site or from sources of contamination external to the site.

GAP recommendations:

- Assess the risk of contaminating produce from chemical and biological hazards present in or near the site for each horticultural activity; keep a record of any significant hazards identified.
- Where a significant risk of chemical or biological contamination has been identified, do not use the site for horticultural production or take remedial action to manage the risk. Soil remediation is possible, but it is expensive and laborious, and requires proper assessment of the type of contaminant to ensure its effectiveness.
- If remedial action is required to manage the risk, monitor actions to check that contamination of produce does not occur.
- Report the location of any sites identified as unsuitable for horticultural production, and refer to local authorities for appropriate action.
- Exclude entry of farm animals in the site for 3 months before planting and during crop production, particularly for crops grown in or close to the ground.
- Position the greenhouse in consideration of prevailing winds and solar radiation, to ensure optimal environmental conditions inside the structure, where possible avoiding flood sites or sites that may be exposed to water runoff.



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Plate 3
Trials in greenhouse tomato

Planting materials: seeds, varieties or rootstocks

Food safety hazard: Chemical and biological contamination of produce from pesticides used during production of planting material.

GAP recommendations:

- Use certified and good quality seeds or planting material if possible (special consideration should be given to the advantages and disadvantages of using GMO seeds, when applicable).
- Keep a record of the name of the supplier of planting material and the date of purchase.
- If planting material is produced on the farm, keep a record of any chemical treatments used.

Fertilizers and soil additives

Food safety hazard: Chemical and biological contamination of produce from fertilizers and soil additives applied directly to the soil or growing medium or through irrigation systems or foliar spraying.

GAP recommendations:

- Assess the risk of chemical and biological contamination of produce from the use of fertilizers and soil additives for each horticultural activity; keep a record of significant hazards identified.
- Where there is significant risk of contamination from heavy metals, select fertilizers and soil additives to minimize the risk and take measures to minimize uptake.
- Where there is significant risk of biological contamination from organic materials, take measures to manage the risk.
- Do not apply untreated organic materials in situations where there is a significant risk of contaminating produce.
- Where an organic material requires treatment on site before use, record the date and treatment method.
- Locate and construct composting sites and compost storage sites to prevent contamination of greenhouse cultures and water sources.
- Where an organic material requires treatment before purchase, obtain documentation from the supplier specifying that the material has been treated to minimize the risk of contaminating produce.
- Do not apply organic materials (untreated or treated) where direct contact with the crop can occur.
- Do not use human sewage for production of fresh produce.
- Store and dispose of fertilizers and soil additives in a manner that does not present a risk of contaminating produce or attracting pests and animals.
- Record applications of fertilizers and soil additives, detailing: name of product and material, date, treatment location, quantity applied, application method and operator name.



WWW.PADVALAGRICULTURE.COM/2008/08/
BRINJAL-VEGETABLE-FARMING.HTML

Plate 4

Do not apply organic materials when direct contact with edible parts of the crop can occur

Irrigation water

Food safety hazard: Chemical and biological contamination of produce from contaminated water used for irrigation.

GAP recommendations:

- Assess the origin of water used for irrigation and the potential for contamination.
- Prefer water of safe quality, e.g. from protected deep wells.
- Use safe quality water during growth stages and potable water near to harvest and consumption.
- Use irrigation drip in preference to spray to reduce exposure.
- Assess the risk of chemical and biological contamination of produce from water used for irrigation for each horticultural activity, and keep a record of any significant hazards identified.
- Where water testing is required to assess the risk of produce contamination, conduct tests at a frequency appropriate to the conditions impacting on the water supply and the horticultural activity, and keep a record of test results.
- Where there is high risk of chemical and biological contamination, either use a safe alternative water source or treat and monitor the water and keep a record of the monitoring results.
- Maintain wells, tanks and irrigation ditches and pipes in good working condition to avoid water stagnation.
- Review existing practices and crop growing conditions to identify potential sources of contamination.
- If feedlots, animal pastures and dairy operations are in the region, use and maintain fences or other barriers to minimize animal access to shared water sources.
- Find out if manure is applied by many farms in the region.
- Find out how local rainfall patterns and topography affect the likelihood that contaminated runoff from these operations will reach surface waters available for irrigation.

Pesticides (agrochemicals)

Biological food safety hazard: Biological contamination of produce from contaminated water used to apply pesticides.

GAP recommendations:

- Where pesticides are applied to the edible part of a product within 2 days of harvest, assess the risk of biological contamination and keep a record of any significant hazards identified.
- Where the risk of biological contamination is significant, either use a safe alternative water source or treat and monitor the water, keeping a record of the results.

Pesticides (agrochemicals) (cont'd)

Chemical food safety hazard: Chemical contamination of produce above maximum residue levels (MRLs) during storage, application and disposal of pesticides used for crop protection.

GAP recommendations:

- Train farm managers and workers to a level appropriate to their area of responsibility for pesticide application.
- Where possible use integrated pest management systems and non-chemical products to minimize the use of chemicals (Table 1, Plate 5).
- Use pesticides approved for the targeted crop; apply according to label directions or in line with a permit issued by a government authority, and at intervals so as to prevent residue levels in excess of the MRL.
- For produce exported to another country, verify approval of chemicals and MRL in the destination country prior to use.
- Use pesticide mixtures only with compatible chemicals and low risk of excessive residues.
- Observe withholding periods between pesticide application and harvest.
- Calibrate equipment used to apply pesticides at least annually and carry out regular maintenance.
- Wash equipment after each use and dispose of washing waste so as to present no risk of contaminating produce.
- Dispose of surplus application mixes so as to present no risk of contaminating produce.
- Store all chemicals in a structurally sound, secure area according to label directions, and in a location chosen to minimize the risk of contamination of sites, water source, packaging materials and produce.
- Dispose of chemicals that are unusable or no longer approved in legal off-farm areas, or label clearly and isolate them from other chemicals.
- Record applications of chemicals for each crop, detailing: chemical used, application date, treatment location, application rate, application method, withholding period and operator name.
- Keep a record of chemicals purchased, detailing: chemical name, place of purchase, date received, quantity purchased, and expiry or manufacture date.
- Keep an up-to-date list of chemicals approved for use on the produce grown on the farm or sites and use to assist in pesticide selection.
- If chemical residues in excess of the MRL are detected, quarantine the crop and carry out a risk assessment to decide whether produce can be consumed; investigate the cause of the contamination and take actions to prevent re-occurrence.



Plate 5
Reduction of hazard in controlling leafminer (Liriomyza trifolii)

Harvesting and handling produce

Equipment, materials and containers

Food safety hazard: Chemical, biological and physical contamination of produce resulting from inappropriate use, cleaning or maintenance of equipment, materials and containers.

GAP recommendations:

- Use equipment, containers and materials which come into contact with produce made of non-toxic substances.
- Clearly mark containers used for storage of waste, chemicals and other dangerous or contaminated substances and do not use for holding produce.
- Regularly clean and maintain equipment to minimize contamination of produce.
- If used seasonally or for different crops or plant parts, clean and sanitize equipment, materials and containers before reuse.
- Store harvest and packing containers and materials in separate areas from chemicals, fertilizers and soil additives, and take measures to minimize contamination from vermin.
- Check harvest and packing containers for soundness and cleanliness before use and clean or discard as required.
- After packing, do not place containers in direct contact with soil and water.

Buildings and structures

Food safety hazard: Chemical, biological and physical contamination of produce from inadequate construction and maintenance of buildings and structures.

GAP recommendations:

- Locate buildings and structures used for growing, packing, handling and storage in areas not prone to environmental contamination (e.g. flooding or toxic emanations) and construct and maintain them to minimize the risk of contaminating produce.
- If used seasonally or as part of a temporary structure, clean and sanitize internal structures before reuse.
- Segregate grease, oil, fuel and farm machinery from handling, packing and storage areas to prevent contamination of produce.
- Design and construct septic, waste disposal and drainage systems to minimize the risk of contaminating the water supply.
- Install shatter-proof lights above areas where produce and packing containers and materials are exposed or protect with shatter-proof covers; or, in the event of a light breaking, reject exposed produce and equipment and clean packing containers and materials.
- Where workshop equipment is located in the same building as handling, packing and storage areas, screen with a physical barrier or do not operate during packing, handling and storage of produce.
- Remove and store or dispose of plant waste so that it does not attract animals and pests in greenhouses, including birds.

Harvesting and handling produce (cont'd)

Cleaning

Food safety hazard: Chemical, microbial and physical contamination of produce resulting from inadequate cleaning of equipment, containers, materials and areas where produce is packed, handled and stored.

GAP recommendations:

- Prepare and follow instructions for and monitor cleaning of equipment, containers and materials that come into contact with produce and areas where produce is packed, handled and stored.
- Use suitable cleaning chemicals at the appropriate concentration (and where relevant, disinfectants specific to surfaces or equipment) to minimize the risk of chemical contamination of produce.

Animals and pest control

Food safety hazard: Biological contamination of produce from vermin infestation, birds and animals and chemical contamination from vermin-control chemicals.

GAP recommendations:

- Take measures to minimize the presence of vermin in and around growing, handling, packing and storage areas.
- Take measures to remove waste and garbage regularly and safely so that it does not attract animals and pests.
- Take measures to discourage birds roosting above growing, handling, packing and storage areas.
- Do not allow domestic animals where produce is grown, handled, packed and stored.
- Locate and maintain baits and traps used for vermin control so as to prevent chemical contamination of produce and packing containers and materials; record the location.

Produce treatment

Food safety hazard: Chemical contamination of produce above the MRL during storage, application and disposal of chemicals applied after harvest.

GAP recommendations:

- After harvest, apply chemicals (including pesticides, fungicides and waxes) approved for the produce and according to label directions or to a permit issued by a government authority.
- For produce exported to another country, verify approval of the chemical and the MRL in the destination country prior to use.
- Regularly clean and calibrate equipment used to apply chemicals and maintain in good working condition.
- Dispose of surplus application mixes and washing waste so as to not risk contaminating produce.
- Store all chemicals in a structurally sound, secure area according to label directions; choose the location to minimize the risk of contamination of sites, water sources, packaging materials and produce.
- Dispose of chemicals that are unusable or no longer approved in legal off-farm areas; or clearly mark and isolate from other chemicals.
- Record applications of chemicals for each type of produce, detailing: chemical used, application date, batch of produce treated, application rate, application method and operator name.
- Keep a record of chemicals purchased, detailing: chemical name, place of purchase, date received, quantity purchased, and expiry or manufacture date.
- Keep an up-to-date list of chemicals approved for post-harvest application to produce.
- If chemical residues in excess of the MRL are detected, quarantine the produce, investigate the cause of contamination and take actions to prevent re-occurrence.

Water use

Food safety hazard: Chemical and biological contamination of produce from contaminated water used after harvest for handling, washing and treating produce.

GAP recommendations:

- Assess the risk of chemical and biological contamination from water used after harvest for handling, washing and treating produce before use and take remedial action if required; keep a record of any significant hazards identified.
- Where water testing is required to assess the risk of produce contamination, conduct tests at a frequency appropriate to the conditions impacting on the water supply and the type of produce, and keep a record of test results.
- Use water of potable standard (WHO guidelines, suitable for drinking) for final wash water applied to the edible parts of produce.
- Adopt appropriate wash methods: vigorously washing produce is more effective for hazard removal; for easily bruised produce, other options are available, including submersion and spray.
- Carry out a series of washes for maximum effect: an initial wash may be useful for removal of the bulk of field soil; successive washes contain a sanitizer or antimicrobial.
- Use the most suitable temperature for wash water. In general, wash water should not be cooler than the produce being washed, so as to prevent risk of infiltration due to temperature differentials.
- Consider alternative treatments for water-sensitive produce.
- Avoid use of dump tanks and spread of contamination: minimize the accumulation of organic material in wash water by regular water changes and appropriately used sanitizers.
- If water is being reused, sanitize the waterflow which should be counter to the movement of produce through the different operations, in order that the most processed produce is always exposed to the cleanest water.
- If ice or water are adopted for cooling to reduce temperature, use potable water. Ensure routine water-quality testing of ice or water intended for use with fresh produce.
- Follow good manufacturing practices (GMPs) to minimize microbial contamination from processing water.
- Limit the presence of water (pooling on floors and surfaces, and condensation in packing area, storage and chillers) as it is a potential source of *Listeria*.



DO KIM CHUNG, VIET NAM

Plate 6
Washing vegetables in pond with rubbish everywhere

Personal hygiene

Food safety hazard: Biological contamination of produce from poor personal hygiene and inadequate facilities.

GAP recommendations:

- Provide instructions, preferably written, on personal hygiene practices to farm workers.
- Train farm workers in personal hygiene practices and keep a record of training where possible.
- Make toilets and hand-washing facilities readily available to farm workers.
- Make available separate areas for taking food and breaks.
- Make workers aware that specific diseases (diarrhoea, infected wounds) may cause food contamination if they come into direct contact with the final fresh product; consequently, in the case of illness, allow workers to work on other activities without prejudice.
- Do not allow casual visitors on site, restrict children's access (hazards of Hepatitis A in endemic areas).

Storage and transport

Food safety hazard: Chemical, biological and physical contamination of produce resulting from inappropriate storage and transport.

GAP recommendations:

- Do not place packed containers in direct contact with soil, and do not expose them to heat or sunshine.
- Where pallets are used, check prior to use for possible contamination from soil, chemical spills, foreign objects and vermin infestation; if unsuitable, reject them and clean or cover with protective material.
- Check transport vehicles before use for cleanliness, foreign objects and vermin infestation; clean them if there is a significant risk of contaminating produce.
- Store produce and transport separately from goods that are a potential source of chemical, biological and physical contamination (beware of goods or inputs transported previously in the same container or vehicle).
- Monitor temperature and duration in storage and transport.



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Plate 7
Packed vegetables ready for market, Iraq

Farm and product management

GAP recommendations:

- Train farm workers in their area of responsibility relevant to GAP and, when possible, keep a record of training.
- Clearly mark packed containers to enable traceability of produce to the farm or site where produce is grown.
- Keep a record of the date of supply and destination for each batch of produce.
- Where produce is identified as being contaminated or potentially contaminated, isolate it and prevent distribution; if sold, notify the buyer immediately.
- Investigate the cause of contamination, take action to prevent re-occurrence and keep a record.
- Check all practices at least once a year to ensure they are done correctly and take action to correct any deficiencies identified.
- Keep a record of practices checked and any corrective actions taken.
- Keep records demonstrating GAP at least for the duration of the production and marketing of the crop, or for longer if required by legislation.

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Session 7: Produce quality module (ppt).

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Session 8: Sources of contamination from food safety hazards (document).

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ColeACP materials

The importance of hygiene.

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21. Labelling and certification: integrated farm assurance with fruit and vegetable production

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INTRODUCTION

The challenge of globalizing markets is nowhere greater than in the primary food sector. GLOBALG.A.P. is an equal partnership of agricultural producers and retailers and has established itself as a key reference for good agricultural practice (GAP) in the global marketplace, becoming a widely used and acceptable GAP standard.

GLOBALG.A.P. is a private sector body that sets voluntary standards for the certification of agricultural products around the globe. The aim is to establish one standard for GAP with different product applications capable of fitting the whole of global agriculture. GLOBALG.A.P. is a global scheme and a reference for good agricultural practices managed by the GLOBALG.A.P. Secretariat. It includes topics such as integrated crop management (ICM), integrated pest control (IPC), quality management system (QMS), hazard analysis and critical control points (HACCP), workers' health, safety and welfare, environmental pollution and conservation management.

Several on-farm assurance systems were in place in many countries prior to the existence of GLOBALG.A.P. (formerly known as EUREPGAP). Due to consumer demands, it was necessary to find a way to encourage the development of regionally adjusted management systems in order to prevent farmers from having to undergo multiple audits. Existing national or regional farm assurance schemes that have successfully completed their benchmarking process are recognized as equivalent to GLOBALG.A.P.

More specifically, the GLOBALG.A.P. Integrated Farm Assurance (IFA) standard (version 4) is a pre-farmgate standard or on-farm standard that covers the certification of the whole agricultural production process of the product: from farm inputs (e.g. feed or seedlings) and all farming activities until the product leaves

the farm. The information in this report is derived from the GLOBALG.A.P. IFA standard (version 4). A business-to-business label, the standard is not directly visible to consumers; it provides the standard and framework for independent, recognized third party certification of farm production processes based on the ISO/IEC Guide 65 (management system standard issued by the International Standards Organization through which independent certification bodies are accredited). The standard comprises a set of normative documents: GLOBALG.A.P. General Regulations, GLOBALG.A.P. Control Points and Compliance Criteria, and GLOBALG.A.P. Checklist (Web site: www.globalgap.org).

The IFA Control Points and Compliance Criteria (CPCC) document is organized in modules to cover various areas or levels of activity on a production site:

- “Scopes” – covering more generic production issues, classified more broadly as:
 - All Farm Base (AF)
 - Crops Base (CB)
 - Livestock Base (LB)
 - Aquaculture Module (AB)
- “Sub-scopes” – covering more specific production details, classified by product type. Specifically, AF and CB are classified as follows:
 - Fruit and Vegetables (FV)
 - Combinable Crops (CC)
 - Coffee (green) (CO)
 - Tea (TE)
 - Flowers and Ornamental (FO)

Only products included in the GLOBALG.A.P. product list may be certified. Fruits and vegetables cultivated outdoors or in greenhouses are included in the list and are eligible for certification.

CERTIFICATION OPTIONS

The options available for certification depend on the constitution of the legal entity applying for certification.

Individual certification (Option 1)

- Individual producer applies for certification (GLOBALG.A.P. or a benchmarked scheme).
- Individual producer is the certificate holder once certified.
 - Multisite without implementation of a quality management system (QMS): individual producer or one organization owns several production

locations or management units which do not function as separate legal entities.

- Multisite with implementation of a QMS: individual producer or one organization owns several production locations or management units which do not function as separate legal entities, but where a QMS has been implemented; in this case, General Regulations Part II – QMS Rules apply.

Multisites with QMS and producer groups (Option 2)

- Producer group applies for group certification (GLOBALG.A.P. or benchmarked scheme).
- The group, as a legal entity, is the certificate holder once certified.
- A group must have a QMS implemented and comply with General Regulations Part II – QMS Rules.

Benchmarked schemes

The certification categories under benchmarked schemes are explained in the GLOBALG.A.P. Benchmarking Regulations.

REGISTRATION PROCESS

Certification bodies/ farm assurers ¹

The applicant chooses a GLOBALG.A.P.-approved certification body (CB) – contact information on approved and provisionally approved CBs is available on the GLOBALG.A.P. Web site; it is the responsibility of the applicant to verify whether the chosen CB is approved for the relevant scopes. The applicant must register with an approved CB or farm assurer as the first step towards obtaining a GLOBALG.A.P. certificate. Unless the applicant has specifically assigned a farm assurer, the CB is the farm assurer by default and is responsible for registration, data updates and collection of fees.

Registration

General

The application must include the information detailed in Annex I.2 (GLOBALG.A.P. Registration Data Requirements), and registration automatically commits the applicant to comply with the obligations laid out therein, including:

¹ GLOBALG.A.P.-approved farm assurers are organizations (producer group organizations, standard owners, consultants etc.) that have signed a license agreement with GLOBALG.A.P. and acquired the right from producers to upload and register these producer activities in the GLOBALG.A.P. database. The service includes the first registration and any subsequent modifications as well as settings of links in the database. The approved farm assurer must be granted these rights in writing from the producer or other legal entity in the GLOBALG.A.P. system.

- compliance with certification requirements at all times;
- payment of the applicable fees established by GLOBALG.A.P. and the CB;
- communication of data updates to the CB;
- compliance with the terms and conditions of the Sub-License and Certification Agreement.

This information will be used by GLOBALG.A.P. to supply the applicant with a unique GLOBALG.A.P. number (GGN). The GGN identifies the applicant with regard to GLOBALG.A.P. activities and is not related to the product or certification status.

Any objective evidence pointing to misuse of the GLOBALG.A.P. claim shall lead to the exclusion of the applicant from certification for 12 months. Such applicants will be listed and the list must be checked before registration in the database. Any case of misuse shall be communicated to GLOBALG.A.P. members.

Confidentiality, data use and data release

- During registration applicants give written access to FoodPLUS² and the certification bodies to use the registration data for internal processes and sanctioning procedures.
- All data in the GLOBALG.A.P. database is available to GLOBALG.A.P., the certification body and the farm assurer with which the producer or producer group is working, and can be used for internal processes and sanctioning procedures.
- Minimum and obligatory data release level for all sub-scopes (and scopes for aquaculture): GGN, registration no., GLOBALG.A.P. certificate no., scheme, version, option, CB, products and status, produce handling/processing declaration, number of producers (for groups), country of production and destination, production management units and produce handling units, information on parallel production and harvest exclusion per product (if applicable) are available to the public. Every certificate holder's company name and address is available to registered industry market participants including GLOBALG.A.P. members.
- If an applicant (or group member) does not agree to the minimum release, it is in breach of the Sub-License and Certification Agreement and cannot be certified, nor may it belong to a producer group seeking certification.
- No data (other than that specified above) may be released by GLOBALG.A.P. or CBs to any other party without the written consent of the applicant.

² FoodPLUS GmbH is a German limited company set up to act as the Secretariat for GLOBALG.A.P.; it ensures independence in the operation of GLOBALG.A.P. standards and is a not-for-profit company.

- Information on the sector-specific requirements is included in the Data Use and Release Agreement on the Web site.

The service contract between the CB and producer may be valid for up to 4 years, with subsequent renewal for periods of up to 4 years. An applicant:

- may not register the same product with different CBs.
- may not register the same product under different certification options.
- may register different products with different CBs and different certification options (e.g. it is possible to register apples under Option 1 and cherries under Option 2, apples with one CB and cherries with another, or both crops with the same CB.).
- may not register production management units (PMU) or group members in different countries with any CB (the GLOBALG.A.P. Secretariat may grant exceptions on a case-by-case basis or within national interpretation guidelines).

The PMU is a production unit (farm, field, orchard, herd, greenhouse etc.) defined by the producer for units where segregation of output (agricultural products) is intended and all provisions have been made and put in place to keep separate records and prevent mixing in the case of parallel production. PMUs that can be considered to operate independently (based on factors such as geography, management and storage facilities) shall be registered in the GLOBALG.A.P. database and indicated on the certificate.

Registration with a new CB

When a producer that has already been registered changes CB or applies to a new CB for certification of a different product, the producer must communicate the GGN assigned by GLOBALG.A.P. to the new CB. Failure to do this will result in a surcharge of the registration fee of € 100 to an Option 1 producer and € 500 to an Option 2 producer group.

Certificate holders who are sanctioned cannot change CB until the outgoing CB closes out the corresponding non-conformance or until the sanction penalty period is over. Individual producer members of a producer group are not allowed to leave the group and register with another group (for the products registered) if there is any pending sanction on the producer issued by the group, or there are any issues relevant to the producer raised by the CB that have not been closed out.

Acceptance

For registration to be accepted, the applicant must:

- submit to the CB the relevant application with all the necessary information (having formally committed to comply with the obligations indicated above).

- sign acceptance of the Sub-License and Certification Agreement with the CB (the applicant shall explicitly acknowledge receipt and inclusion of the Sub-License and Certification Agreement with his/her signature on the service contract/agreement with the CB, and the CB must hand over a copy of the agreement to the producer).
- be assigned a GLOBALG.A.P. number (GGN).
- pay the GLOBALG.A.P. registration fee (as explained in the current GLOBALG.A.P. fee table available on the GLOBALG.A.P. Web site).

The registration and acceptance process must be finalized before inspection can take place. For first registration, the CB shall confirm the acceptance of the application and provide the applicant with the GGN within 14 calendar days of receipt of the completed application.

Application and certification scope

Any producer of primary agricultural products covered by GLOBALG.A.P. standards may apply for GLOBALG.A.P. certification. For GLOBALG.A.P. certification, the term “producers” is defined as follows: a person (individual) or business (individual or producer group) who is legally responsible for the production of the products relevant to the scope, and who has the legal responsibility for the products sold by that farming business.

Standards covered by GLOBALG.A.P. certification

- Only products covered by the GLOBALG.A.P. product list, published on the GLOBALG.A.P. Web site, can apply for certification.
- GLOBALG.A.P. certification covers the controlled production process of primary products and does not cover wild/catch, wild fish/catch or crops harvested in the wild.
- Refer to the standard-specific rules (published with the CPCC) for possible exceptions to the General Regulations contained in this document and for new standards released.

All standards

Producers cannot receive certification for products not produced by them. Parallel production/ownership (of certified and non-certified products) is possible when additional rules are implemented.

Integrated farm assurance: fruit and vegetables

GLOBALG.A.P. certification covers fruit and vegetables used for fresh, cooked or processed consumption by humans. Vegetables used solely for medicinal or aromatic purposes cannot be certified.

Note that other standards are certified (e.g. combinable crops for cooked or processed consumption by humans or animals or for use in the industry, flowers and ornamentals, livestock scope, plant propagation material, compound feed in manufacturing and aquaculture scope).

Applicable CPCC scopes and modules in integrated farm assurance

It is not possible to certify the respective sub-scope without also verifying compliance to the applicable scope. The inspection of compliance criteria of the scope must be interpreted according to the sub-scope applied for. Any certification applied for that introduces additional sub-scopes into an existing certificate must have the scope inspected, taking into account the additional sub-scopes concerned.

The scopes are automatically coupled to the sub-scopes according to the choice of sub-scopes applied for. For more information on the structure and modular approach, read the introduction to the CPCC document.

Burden of proof

If information concerning a GLOBALG.A.P.-certified-producer with a potential impact on the certified status or claim (e.g. MRL exceedance, microbial contamination) is transmitted to the GLOBALG.A.P. Secretariat, it is the responsibility of the producer to refute the claim by verifying and providing evidence for compliance with the GLOBALG.A.P. standard:

- If the CB conducts the investigation, the findings and actions taken will be reported to the GLOBALG.A.P. Secretariat.
- If the retailer or owner of the product conducts their own investigation, they shall report the findings back to the GLOBALG.A.P. Secretariat who in turn will ask the CB to take appropriate action.
- GLOBALG.A.P. will give the producer a certain amount of time to do this.
- If the CB does not deem the evidence supplied by the legal entity (producer or produce handling unit, PHU) adequate, the CB will issue a sanction and follow the normal sanctioning procedures as described in GLOBALG.A.P. General Regulations.
- Producers must have full traceability in place – this could include mass balance, chain of custody certification and any other records needed to verify and check the case. Should the evidence include laboratory analyses, accredited laboratories (ISO 17025) and independent sampling (according to the rules as set out in the relevant CPCC) must be included.

ASSESSMENT PROCESS

In order to achieve certification, a registered party must perform either a self-assessment (Option 1 and Option 1 multisite without QMS) or internal inspections (Option 1 multisite with QMS and Option 2) and receive external inspections by the chosen certification body.

Option 1 – single sites and multisites without QMS

This section is applicable to applicants that are single legal entities (individual producer or company) with single production sites (farm) or multiple production sites that are not separate legal entities and are all centrally managed by the applicant. Table 1 presents a summary of the assessments to be undertaken before a certificate is issued (initial evaluation) and annually thereafter (surveillance evaluations).

Self-assessments

The self-assessment shall:

- cover all sites, products and processes under the certification scope and comply with the requirements set in the applicable control points;
- be the responsibility of the producer;
- be carried out at least annually before the initial or surveillance inspections against the complete checklist (Major and Minor Musts and Recommendations) of all relevant scope(s) and sub-scope(s) and registered areas; the completed checklist must be available on site for review at all times;
- record comments and positive findings during the self-assessment as described by the checklist.

External inspections

The inspection (announced and unannounced) shall be carried out by a CB inspector or auditor. The CB shall inspect the complete checklist (Major and Minor Musts and Recommendations) of the applicable scope(s) and sub-scope(s).

Announced inspections

Each applicant shall undergo one announced external inspection at the initial assessment and thereafter once a year.

TABLE 1
Assessments (Option 1 – single sites and multisites without QMS)

	Initial evaluations (first year)	Subsequent evaluations
Self-assessments by producer	Entire scope (all registered sites)	Entire scope (all registered sites)
Externally by the CB	Announced inspection of entire scope (all registered sites)	1. Announced inspection of entire scope (all registered sites) 2. Unannounced inspection of (minimum 10% of certificate holders)

The inspection shall cover:

- all accepted products;
- all registered production locations;
- all registered product handling sites (in IFA).

External unannounced surveillance inspections

The CB shall carry out unannounced surveillance inspections on a minimum of 10 percent of all producers certified under Option 1.

Unless the GLOBALG.A.P. Secretariat has approved a shortened checklist, the CB shall inspect the Major and Minor Musts of the applicable scope(s) and sub-scope(s). Any non-compliance will be handled in the same way as for non-compliances found during an announced inspection.

The CB will inform the producer in advance of the intended visit; notification will not normally exceed 48 hours (2 working days). If impossible for the producer to accept the proposed date (for medical or other justifiable reasons), the producer will have one more opportunity to be informed of an unannounced surveillance inspection. The producer shall receive a written warning if the first proposed date is not accepted; the producer will then receive another 48-hour notification of a visit; if this visit cannot take place for non-justifiable reasons, a suspension of all products will be issued.

Option 2 and Option 1 multisite with QMS

This section is applicable to groups and individuals with multiple sites who have implemented a QMS and who comply with the requirements laid down in Part II of the General Regulations. The applicant is responsible for ensuring that all producers and PMUs under the certification scope comply with the certification requirements at all times. The CB does not inspect all producers or PMUs, but just a sample. Thus it is not the responsibility of the CB to determine the compliance of each producer or PMU (this responsibility rests with the applicant). The CB must assess whether the applicant's internal controls are appropriate. Table 2 presents a summary of the assessments to be undertaken before a certificate is issued (Initial Evaluation) and annually thereafter (Surveillance Evaluation).

Internal assessments

The applicant shall undertake internal assessments of all producers and PMUs to ensure compliance with the certification requirements. Internal assessments shall comply with requirements laid down in Part II and include:

- a minimum of one internal audit of the QMS carried out by the internal auditor before the first CB audit and thereafter once a year;

TABLE 2

Assessments (Option 2 and Option 1 multisite with QMS)

	Initial evaluations (first year)	Subsequent evaluations
Internally by the producer group and Option 1 multisite operation with QMS	<ol style="list-style-type: none"> 1. Internal QMS audit 2. Internal inspection of each producer and/or PMU and PHU 	<ol style="list-style-type: none"> 1. Internal QMS audit 2. Internal inspection of each producer and/or PMU and PHU
Externally by the CB	<ol style="list-style-type: none"> 1. Announced QMS audit 2. Unannounced inspection to (minimum) square root of producer members and/or PMUs and PHUs 3. Unannounced inspection to (minimum) 50% square root of producers and/or PMUs and PHUs 	<ol style="list-style-type: none"> 1. Announced QMS audit 2. Unannounced QMS audit to 10% of certificate holders 3. Announced inspection to (minimum) square root of actual number of producers and/or PMUs and PHUs minus the number inspected unannounced during previous cycle 4. Unannounced inspection to (minimum) 50% square root of actual number of producers and/or PMUs

- a minimum of one internal inspection of each registered producer/PMU and PHU (produce handling unit) carried out by the internal inspector before the first CB inspection and thereafter once a year;
- self-assessments by each member of the group (but only if an internal requirement – it is not a GLOBALG.A.P. requirement).

External quality management system (QMS) audit

The audit (announced and unannounced) shall be carried out by a CB auditor (see CB auditor requirements in Part III of General Regulations). The audit (announced and unannounced) shall be based on the QMS checklist available on the GLOBALG.A.P. Web site.

QMS announced audits

The CB shall carry out one announced external audit of the QMS at the initial assessment and thereafter once a year.

QMS unannounced surveillance audits

The CB shall carry out additional QMS unannounced external audits on a minimum of 10 percent of the certified producer groups and multisites annually. Non-compliance detected will be handled as for an announced audit; non-conformances will lead to a sanction applied to the whole group or multisite.

The CB will inform the certificate holder. This notification will normally not exceed 48 hours (2 working days) in advance of the intended visit. If it is impossible for the certificate holder to accept the proposed date (for medical or other justifiable reasons), the certificate holder will receive one more chance to be informed of an unannounced surveillance inspection. The certificate holder shall receive a written warning if the first date is not accepted. The certificate holder will receive another 48-hour notification of a visit. If the visit cannot take place for non-justifiable reasons, a complete suspension will be issued.

External producer or site inspections

A CB inspector or auditor shall carry out the inspections. The CB shall inspect the complete checklist (Major and Minor Musts and Recommendations) of the applicable scope(s) and sub-scope(s) during ALL inspections.

- **Initial inspection.** As a minimum, the square root (or next whole number rounded upwards if there are any decimals) of the total number of producers and production sites in the certification scope must be inspected before a new certificate can be issued (initial certification or inspection by a new CB).
- **Surveillance producer inspections.** The CB shall carry out announced external inspections of each producer group and multisite annually. The minimum number of producers to be inspected per certificate holder depends on the outcome of the previous unannounced inspections and QMS audit.

The minimum number of producers/sites to be inspected during a certification cycle shall be equivalent to the square root of the current number of producers/sites (grouped by type of activity). The inspections shall be divided in two: 50% unannounced during the validity period of a certificate (12 months); the other 50% during the announced surveillance inspection.

Only if the producers inspected externally have no other sanctions raised in that surveillance inspection, the following regular announced inspection by the CB will be reduced to the square root of the current number of producers/PMUs minus the number of producers/PMUs inspected unannounced (providing the findings from the QMS audit carried out at the following regular announced inspection are also favourable to this reduction).

Before a certification decision can be made, the square root of the total number of current producer members and PMUs must have been inspected in the previous 12 months.

CERTIFICATION PROCESS

Explanation of terms

- **Non-compliance (of a control point):** A GLOBALG.A.P. Control Point in the checklist is not fulfilled according to the Compliance Criteria (e.g. the producer does not comply with the Minor Must AF).
- **Non-conformance (of the GLOBALG.A.P. Certification Rules):** A GLOBALG.A.P. Rule necessary for obtaining the certificate is breached.
- **Contractual non-conformances:** An agreement signed in the contract between the CB and the producer related to GLOBALG.A.P. issues is breached.

CCPCC

Requirements to achieve and maintain GLOBALG.A.P. Certification Control Points and Compliance Criteria consist of three types of control points: Major Musts, Minor Musts and Recommendations. In order to obtain GLOBALG.A.P. certification, the requirements are as follows:

- Major Musts: 100% compliance of all applicable Major Must and QMS control points is compulsory.
- Minor Musts: 95% compliance of all applicable Minor Must control points is compulsory.
- Recommendations: No minimum percentage of compliance.

Comments shall be supplied for all non-compliant and not applicable Major and Minor Must control points. In addition, comments shall also be supplied for all Major Musts, unless otherwise indicated on the checklist. This is obligatory for internal as well as external assessments.

For example, a producer seeking certification for fruit and vegetables needs to comply with 100% of applicable Major Musts and 95% of the applicable Minor Musts of the All Farm (AF), Crops Base (CB) and Fruit and Vegetables (FV) modules combined.

Certification decision

The CB shall make the certification decision within a maximum of 28 calendar days after closure of any outstanding non-conformances.

Any complaints or appeals against CBs will follow the CB's own complaints and appeals procedure, which each CB must have and communicate to its clients. Should the CB not respond adequately, the complaint can be addressed to the GLOBALG.A.P. Secretariat using the GLOBALG.A.P. complaints extranet, available on the GLOBALG.A.P. Web site (www.globalgap.org).

Sanctions

Sanctions shall be forced as described below:

- When a non-conformance is detected, the CB shall apply a sanction (Warning, Suspension of a product or Cancellation).
- Producers are not permitted to change CB until the non-conformance which led to the respective sanction is satisfactorily closed out.
- Only the CB or the producer group which issued the sanction is entitled to lift it; it may only do so if there is sufficient and timely evidence of corrective action.

GLOBALG.A.P. certificate and certification cycle

A certificate is not transferable from one legal entity to another if a production unit changes legal entity: an initial inspection is required.

The certification cycle is 12 months in accordance with any sanctions or extensions (under certain conditions it is possible to extend the certificate validity to 4 months).

Maintenance of GLOBALG.A.P. certification

The registration of the producer and the proposed products for the relevant scopes must be reconfirmed with the CB annually before the expiry date. Otherwise the product status will change from “Certified” to “Certificate not renewed or re-registered”.

OBLIGATION TO APPLY PRODUCT TRACEABILITY AND SEGREGATION

A product meeting the requirements of the GLOBALG.A.P. Standard and marketed as such shall be traceable and handled to avoid contact with non-GLOBALG.A.P.-approved products.

There shall be a documented procedure for the identification of registered products and to enable traceability of all products both conforming and non-conforming to the applicable production sites. A mass balance exercise must be carried out to demonstrate compliance within the legal entity.

Effective systems and procedures shall be in place to avoid risk of mislabelling or mixing of GLOBALG.A.P.-certified and non-GLOBALG.A.P.-certified products.

If a member of the group registers for parallel production, the Traceability and Segregation control points (AF.12) shall be applicable.

For fruit and vegetables certification, the produce handling site shall operate procedures enabling a registered product to be identifiable and traceable from receipt, through handling, storage and dispatch.

RULES FOR USE OF GLOBALG.A.P. AND EUREPGAP TRADEMARK AND LOGO

GLOBALG.A.P. is the owner of the trademarks “EUREPGAP” and “GLOBALG.A.P.” and the logo, collectively the “GLOBALG.A.P. Trademark”. The “EUREPGAP” trademark shall be replaced by the trademark “GLOBALG.A.P.” with further notice. The “EUREPGAP” trademark shall be used until further notice alone or in conjunction with “GLOBALG.A.P.”

GLOBALG.A.P. trademark

Certain rules govern the use of the GLOBALG.A.P. trademark:

- The GLOBALG.A.P. trademark shall never appear on the product, on consumer packaging, or at the point of sale in direct connection to single products.
- Producers may only use the GLOBALG.A.P. trademark on pallets containing only certified GLOBALG.A.P. products and which will not appear at the point of sale.
- GLOBALG.A.P.-certified producers may use the GLOBALG.A.P. trademark in business-to-business communication, and for traceability, segregation or identification purposes on site at the production location.
- GLOBALG.A.P. retailer, associate and supplier members can use the trademark in promotional printouts, flyers, hardware and electronic displays (not directly linked to certified product) and in business-to-business communication.
- GLOBALG.A.P.-approved certification bodies can use the trademark in promotional material directly linked to GLOBALG.A.P. certification activities in business-to-business communication, and on GLOBALG.A.P. certificates they issue.
- The GLOBALG.A.P. trademark shall never be used on promotional items, apparel or accessories of any kind, bags or personal care items, or in connection with retail store services.



Specifications

The EUREPGAP logo and the GLOBALG.A.P. logo must always be obtained from the GLOBALG.A.P. Secretariat. This will ensure that it contains the exact corporate colour and format, as in the box.

FAO TECHNICAL PAPERS

FAO PLANT PRODUCTION AND PROTECTION PAPERS

1	Horticulture: a select bibliography, 1976 (E)	21	Recommended methods for measurement of pest resistance to pesticides, 1980 (E F)
2	Cotton specialists and research institutions in selected countries, 1976 (E)	22	China: multiple cropping and related crop production technology, 1980 (E)
3	Food legumes: distribution, adaptability and biology of yield, 1977 (E F S)	23	China: development of olive production, 1980 (E)
4	Soybean production in the tropics, 1977 (C E F S)	24/1	Improvement and production of maize, sorghum and millet – Vol. 1. General principles, 1980 (E F)
4 Rev.1	Soybean production in the tropics (first revision), 1982 (E)	24/2	Improvement and production of maize, sorghum and millet – Vol. 2. Breeding, agronomy and seed production, 1980 (E F)
5	Les systèmes pastoraux sahéliens, 1977 (F)	25	<i>Prosopis tamarugo</i> : fodder tree for arid zones, 1981 (E F S)
6	Pest resistance to pesticides and crop loss assessment – Vol. 1, 1977 (E F S)	26	Pesticide residues in food 1980 – Report, 1981 (E F S)
6/2	Pest resistance to pesticides and crop loss assessment – Vol. 2, 1979 (E F S)	26 Sup.	Pesticide residues in food 1980 – Evaluations, 1981 (E)
6/3	Pest resistance to pesticides and crop loss assessment – Vol. 3, 1981 (E F S)	27	Small-scale cash crop farming in South Asia, 1981 (E)
7	Rodent pest biology and control – Bibliography 1970-74, 1977 (E)	28	Second expert consultation on environmental criteria for registration of pesticides, 1981 (E F S)
8	Tropical pasture seed production, 1979 (E F** S**)	29	Sesame: status and improvement, 1981 (E)
9	Food legume crops: improvement and production, 1977 (E)	30	Palm tissue culture, 1981 (C E)
10	Pesticide residues in food, 1977 – Report, 1978 (E F S)	31	An eco-climatic classification of intertropical Africa, 1981 (E)
10 Rev.	Pesticide residues in food 1977 – Report, 1978 (E)	32	Weeds in tropical crops: selected abstracts, 1981 (E)
10 Sup.	Pesticide residues in food 1977 – Evaluations, 1978 (E)	32 Sup.1	Weeds in tropical crops: review of abstracts, 1982 (E)
11	Pesticide residues in food 1965-78 – Index and summary, 1978 (E F S)	33	Plant collecting and herbarium development, 1981 (E)
12	Crop calendars, 1978 (E/F/S)	34	Improvement of nutritional quality of food crops, 1981 (C E)
13	The use of FAO specifications for plant protection products, 1979 (E F S)	35	Date production and protection, 1982 (Ar E)
14	Guidelines for integrated control of rice insect pests, 1979 (Ar C E F S)	36	El cultivo y la utilización del tarwi – <i>Lupinus mutabilis</i> Sweet, 1982 (S)
15	Pesticide residues in food 1978 – Report, 1979 (E F S)	37	Pesticide residues in food 1981 – Report, 1982 (E F S)
15 Sup.	Pesticide residues in food 1978 – Evaluations, 1979 (E)	38	Winged bean production in the tropics, 1982 (E)
16	Rodenticides: analyses, specifications, formulations, 1979 (E F S)	39	Seeds, 1982 (E/F/S)
17	Agrometeorological crop monitoring and forecasting, 1979 (C E F S)	40	Rodent control in agriculture, 1982 (Ar C E F S)
18	Guidelines for integrated control of maize pests, 1979 (C E)	41	Rice development and rainfed rice production, 1982 (E)
19	Elements of integrated control of sorghum pests, 1979 (E F S)	42	Pesticide residues in food 1981 – Evaluations, 1982 (E)
20	Pesticide residues in food 1979 – Report, 1980 (E F S)		
20 Sup.	Pesticide residues in food 1979 – Evaluations, 1980 (E)		

43	Manual on mushroom cultivation, 1983 (E F)	72/1	Pesticide residues in food 1985 – Evaluations – Part I: Residues, 1986 (E)
44	Improving weed management, 1984 (E F S)	72/2	Pesticide residues in food 1985 – Evaluations – Part II: Toxicology, 1986 (E)
45	Pocket computers in agrometeorology, 1983 (E)	73	Early agrometeorological crop yield assessment, 1986 (E F S)
46	Pesticide residues in food 1982 – Report, 1983 (E F S)	74	Ecology and control of perennial weeds in Latin America, 1986 (E S)
47	The sago palm, 1983 (E F)	75	Technical guidelines for field variety trials, 1993 (E F S)
48	Guidelines for integrated control of cotton pests, 1983 (Ar E F S)	76	Guidelines for seed exchange and plant introduction in tropical crops, 1986 (E)
49	Pesticide residues in food 1982 – Evaluations, 1983 (E)	77	Pesticide residues in food 1986 – Report, 1986 (E F S)
50	International plant quarantine treatment manual, 1983 (C E)	78	Pesticide residues in food 1986 – Evaluations – Part I: Residues, 1986 (E)
51	Handbook on jute, 1983 (E)	78/2	Pesticide residues in food 1986 – Evaluations – Part II: Toxicology, 1987 (E)
52	The palmyrah palm: potential and perspectives, 1983 (E)	79	Tissue culture of selected tropical fruit plants, 1987 (E)
53/1	Selected medicinal plants, 1983 (E)	80	Improved weed management in the Near East, 1987 (E)
54	Manual of fumigation for insect control, 1984 (C E F S)	81	Weed science and weed control in Southeast Asia, 1987 (E)
55	Breeding for durable disease and pest resistance, 1984 (C E)	82	Hybrid seed production of selected cereal, oil and vegetable crops, 1987 (E)
56	Pesticide residues in food 1983 – Report, 1984 (E F S)	83	Litchi cultivation, 1989 (E S)
57	Coconut, tree of life, 1984 (E S)	84	Pesticide residues in food 1987 – Report, 1987 (E F S)
58	Economic guidelines for crop pest control, 1984 (E F S)	85	Manual on the development and use of FAO specifications for plant protection products, 1987 (E** F S)
59	Micropropagation of selected rootcrops, palms, citrus and ornamental species, 1984 (E)	86/1	Pesticide residues in food 1987 – Evaluations – Part I: Residues, 1988 (E)
60	Minimum requirements for receiving and maintaining tissue culture propagating material, 1985 (E F S)	86/2	Pesticide residues in food 1987 – Evaluations – Part II: Toxicology, 1988 (E)
61	Pesticide residues in food 1983 – Evaluations, 1985 (E)	87	Root and tuber crops, plantains and bananas in developing countries – challenges and opportunities, 1988 (E)
62	Pesticide residues in food 1984 – Report, 1985 (E F S)	88	<i>Jessenia</i> and <i>Oenocarpus</i> : neotropical oil palms worthy of domestication, 1988 (E S)
63	Manual of pest control for food security reserve grain stocks, 1985 (C E)	89	Vegetable production under arid and semi-arid conditions in tropical Africa, 1988 (E F)
64	Contribution à l'écologie des aphides africains, 1985 (F)	90	Protected cultivation in the Mediterranean climate, 1990 (E F S)
65	Amélioration de la culture irriguée du riz des petits fermiers, 1985 (F)	91	Pastures and cattle under coconuts, 1988 (E S)
66	Sesame and safflower: status and potentials, 1985 (E)	92	Pesticide residues in food 1988 – Report, 1988 (E F S)
67	Pesticide residues in food 1984 – Evaluations, 1985 (E)	93/1	Pesticide residues in food 1988 – Evaluations – Part I: Residues, 1988 (E)
68	Pesticide residus in food 1985 – Report, 1986 (E F S)	93/2	Pesticide residues in food 1988 – Evaluations – Part II: Toxicology, 1989 (E)
69	Breeding for horizontal resistance to wheat diseases, 1986 (E)		
70	Breeding for durable resistance in perennial crops, 1986 (E)		
71	Technical guideline on seed potato micropropagation and multiplication, 1986 (E)		

94	Utilization of genetic resources: suitable approaches, agronomical evaluation and use, 1989 (E)	120/1	Weed management for developing countries, Addendum 1, 2004 (E F S)
95	Rodent pests and their control in the Near East, 1989 (E)	121	Rambutan cultivation, 1993 (E)
96	<i>Striga</i> – Improved management in Africa, 1989 (E)	122	Pesticide residues in food 1993 – Report, 1993 (E F S)
97/1	Fodders for the Near East: alfalfa, 1989 (Ar E)	123	Rodent pest management in eastern Africa, 1994 (E)
97/2	Fodders for the Near East: annual medic pastures, 1989 (Ar E F)	124	Pesticide residues in food 1993 – Evaluations – Part I: Residues, 1994 (E)
98	An annotated bibliography on rodent research in Latin America 1960-1985, 1989 (E)	125	Plant quarantine: theory and practice, 1994 (Ar)
99	Pesticide residues in food 1989 – Report, 1989 (E F S)	126	Tropical root and tuber crops – Production, perspectives and future prospects, 1994 (E)
100	Pesticide residues in food 1989 – Evaluations – Part I: Residues, 1990 (E)	127	Pesticide residues in food 1994 – Report, 1994 (E)
100/2	Pesticide residues in food 1989 – Evaluations – Part II: Toxicology, 1990 (E)	128	Manual on the development and use of FAO specifications for plant protection products – Fourth edition, 1995 (E F S)
101	Soilless culture for horticultural crop production, 1990 (E)	129	Mangosteen cultivation, 1995 (E)
102	Pesticide residues in food 1990 – Report, 1990 (E F S)	130	Post-harvest deterioration of cassava – A biotechnology perspective, 1995 (E)
103/1	Pesticide residues in food 1990 – Evaluations – Part I: Residues, 1990 (E)	131/1	Pesticide residues in food 1994 – Evaluations – Part I: Residues, Volume 1, 1995 (E)
104	Major weeds of the Near East, 1991 (E)	131/2	Pesticide residues in food 1994 – Evaluations – Part I: Residues, Volume 2, 1995 (E)
105	Fundamentos teórico-prácticos del cultivo de tejidos vegetales, 1990 (S)	132	Agro-ecology, cultivation and uses of cactus pear, 1995 (E)
106	Technical guidelines for mushroom growing in the tropics, 1990 (E)	133	Pesticide residues in food 1995 – Report, 1996 (E)
107	<i>Gynandropsis gynandra</i> (L.) Briq. – a tropical leafy vegetable – its cultivation and utilization, 1991 (E)	134	(Number not assigned)
108	Carambola cultivation, 1993 (E S)	135	Citrus pest problems and their control in the Near East, 1996 (E)
109	Soil solarization, 1991 (E)	136	El pepino dulce y su cultivo, 1996 (S)
110	Potato production and consumption in developing countries, 1991 (E)	137	Pesticide residues in food 1995 – Evaluations – Part I: Residues, 1996 (E)
111	Pesticide residues in food 1991 – Report, 1991 (E)	138	Sunn pests and their control in the Near East, 1996 (E)
112	Cocoa pest and disease management in Southeast Asia and Australasia, 1992 (E)	139	Weed management in rice, 1996 (E)
113/1	Pesticide residues in food 1991 – Evaluations – Part I: Residues, 1991 (E)	140	Pesticide residues in food 1996 – Report, 1997 (E)
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This publication capitalizes on the experience of scientists from the North Africa and Near East countries, in collaboration with experts from around the world, specialized in the different aspects of greenhouse crop production. It provides a comprehensive description and assessment of the greenhouse production practices in use in Mediterranean climate areas that have helped diversify vegetable production and increase productivity. Guidance is provided on potential areas for improvement of greenhouse cultivation. More specifically the document aims at strengthening technical capacity in the use of Good Agriculture Practices (GAP) as a means to improve product quality and safety, and achieve sustainable production intensification of greenhouse vegetables in countries in Mediterranean climate areas. The publication is also meant to be used as a reference and tool for trainers and growers as well as other actors in the greenhouse vegetables value chain in this region.

